# DEVELOPMENT AND OPTIMIZATION OF ULTRA-HIGH PERFORMANCE CONCRETE USING LOCAL MATERIALS

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**DEVELOPMENT AND OPTIMIZATION OF ULTRA-HIGH PERFORMANCE CONCRETE USING LOCAL MATERIALS**

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| ABC | Accelerated Bridge Construction |
| ACI | American Concrete Institute |
| ASTM | American Society for Technology and Materials |
| CRC | Compact Reinforced Composite |
| DSP | Concrete Densified with Small Particles |
| $f_c$ | Ultimate Compressive Strength |
| FHWA | Federal Highway Administration |
| GDOT | Georgia Department of Transportation |
| HML | Hierarchical Machine Learning |
| HRWR | High Range Water Reducer |
| psi | Pounds Per Square Inch |
| RPC | Reactive Powder Concrete |
| SCM | Supplementary Cementitious Material |
| UHPC | Ultra-high Performance Concrete |

# SUMMARY

Accelerated Bridge Construction (ABC) is a set of design principles that allow for the rapid construction of bridges. In accelerated bridge construction, a material known as ultra-high performance concrete (UHPC) is often used to join structural elements of the bridge together. While the material performs well in accelerated conditions, more widespread adoption of UHPC is often hindered by its high price and the proprietary nature of commercial products. In order to address this issue, a less expensive, non-proprietary UHPC mix design is explored and developed. The research effort described in this thesis includes an experimental quantification of the effects of using various Georgian materials on compressive strength as well as an investigation on scaling the promising mix designs to production-sized batches. Finally, the emerging technology of Hierarchical Machine Learning is used to develop UHPC mix designs based on previously-published data.

# CHAPTER 1. INTRODUCTION

## 1.1 Problem Statement and Research Need

Accelerated Bridge Construction (ABC) is a collection of construction techniques that allows for bridge construction to be greatly accelerated through the use of precast and prestressed elements. The use of precast girders and deck panels necessitates closure pours to fill joints between components. Ultra-high performance concrete (UHPC), a relatively new type of concrete exhibiting enhanced durability, has shown great applicability to ABC construction by minimizing joint widths [1]. These minimized joint widths allow cheaper, faster construction by simplifying formwork and eliminating the need for shoring [2, 3].

Commercially available UHPC has proven successful in field construction, but the cost of commercially available UHPC has inhibited its widespread adoption [4]. Whereas normal concrete costs approximately $100 per cubic yard, commercially available UHPC is patented and costs upwards of $2,000 per cubic yard [4, 5]. To this end, there is considerable interest in developing non-proprietary UHPC mix designs from local materials in order to make it a more cost-effective material.

At the statewide level, UHPC mixes have been made from local materials in Arkansas [6], Colorado [7], Michigan [8], Montana [9], and South Carolina [10], amongst others. To date, however, there has been no evaluation of the suitability of Georgia's natural resources for non-proprietary UHPC development. As the Georgia Department of Transportation (GDOT) looks towards incorporating ABC techniques, a need has arisen for an affordable UHPC mix design capable of being produced locally.

## 1.2 Study Goal and Scope

This thesis addresses the following objectives related to the design of a cost-effective UHPC mix using local materials:

1. Evaluate cement, aggregates, admixtures, and supplementary cementitious materials available in Georgia in order to determine their compatibility with ultra-high performance concrete.
2. Develop a mix design for UHPC made from materials local to Georgia that exceeds a 28-day compressive strength of 18,000 psi.
3. Determine mixing procedures necessary to properly scale the mix from laboratory batches to large-scale production.
4. Investigate utilizing machine learning techniques to inform and accelerate the design of UHPC.

## 1.3 Outline of Thesis

The thesis is divided into six chapters. Chapter 1 gives a general overview of the uses and need for non-proprietary UHPC in Georgia. Chapter 2 provides a literature review on the history and development of UHPC as a class of material, the process of optimizing particle packing, the usage of UHPC in ABC construction, GDOT's work involving UHPC to date, and the suitability of local materials to UHPC. Chapter 3 details the design procedure for developing the non-proprietary UHPC. Chapter 4 provides information about mix design procedures for scaling the mix from benchtop mixers to production-scale batches and provides further information gained on the impact of aggregate fineness on workability of the mixture. Chapter 5 demonstrates how information from the wealth of previous literature on UHPC can used to design UHPC via a machine learning approach. Chapter 6 summarizes the findings from all chapters and provides queries for further research on this topic.

# CHAPTER 2. LITERATURE REVIEW

## 2.1 The Development of UHPC

Ultra-high strength cement pastes were first developed in the early 1970s as researchers explored the potential of very low water to cement (w/c) ratio mixes. Yudenfreund et. al tested mixes with w/c ratios ranging from 0.20 to 0.30 and found that 28-day compressive strengths of up to 29,000 psi were possible [11]. Following these developments, an early precursor to UHPC called Compact Reinforced Composite (CRC) was developed by H.H. Bache in late 1987 [12]. This material was the first in a new class of materials referred to as Densified with Small Particles (DSP) due to its inclusion of superplasticizer and silica fume, which reduced void space and led to a denser concrete. The CRC material also incorporated 4% steel fibers by volume. These fibers served to increase the ductility of the brittle, high-strength cementitious matrices that were developed in earlier research, and a patent for the material was issued in 1990 [13]. The proportional mix design of CRC is given in Table 2-1, where components are given in terms of their weight relative to the weight of the cement included.

**Table 2-1: Mix Proportions of CRC [14]**

| Material | Proportion |
|---|---|
| Portland Cement | 1.0 |
| Fine Sand | 0.92 |
| Silica Fume | 0.25 |
| Glass Powder | 0.25 |
| HRWR | 0.0108 |
| Steel Fibers | 0.22 to 0.31 |
| Water | 0.18 to 0.20 |

UHPC was developed further by researchers in France during the 1990s. Richard and Cheyrezy evaluated the effects of different materials and curing conditions on UHPC during that time [15], while de Larrard and Sedran began work on optimizing the packing density of the unreacted minerals and components [16]. This French research would lead to the development of Reactive Powder Concrete (RPC) [17]. RPC was the first concrete to have optimized packing across the full range of particle sizes in the mix design. From micron-sized silica fume to macro-sized aggregates, the mix was optimized to include as little void space as possible [17]. In 2012 the RPC mix was patented by Lafarge Cement and produced globally under the name Ductal as the first commercially available UHPC-class material. [18]. The mix composition for Ductal is given in Table 2-2.

**Table 2-2: Mix Design of Ductal (RPC) [14]**

| **Material** | **Quantity** | **Proportion** |
|---|---|---|
| Portland Cement | 1,200 lb/yd$^3$ | 1.0 |
| Fine Sand | 1,720 lb/yd$^3$ | 1.43 |
| Silica Fume | 390 lb/yd$^3$ | 0.325 |
| Ground Quartz | 355 lb/yd$^3$ | 0.296 |
| HRWR | 51.8 lb/yd$^3$ | 0.043 |
| Accelerator | 50.5 lb/yd$^3$ | 0.042 |
| Steel Fibers | 263 lb/yd$^3$ | 0.219 |
| Water | 184 lb/yd$^3$ | 0.153 |

Domestic investigations into UHPC development began not long after the development of RPC. In 2007, the United States Army Corps of Engineers patented Cor-Tuf, a UHPC mix developed for use in blast resistant structures [19]. In 2019, the Corps of Engineers sold the rights for commercial production of Cor-Tuf to Cor-Tuf UHPC, a company in

Northern Virginia [20]. The proportional mix composition for Cor-Tuf is given in Table 2-3.

**Table 2-3: Proportional Mix Design of Cor-Tuf**

| Material | Proportion |
|---|---|
| Portland Cement | 1.0 |
| Sand | 0.967 |
| Silica Flour | 0.277 |
| Silica Fume | 0.389 |
| HRWR | 0.0171 |
| Steel Fibers | 0.310 |
| Water | 0.208 |

As interest in UHPC has grown around the United States, much work has been done to develop non-proprietary UHPC mixes. Leading the way has been the Federal Highway Administration (FHWA), who in 2013 published example UHPC mixes that were adjusted for different regions of the United States [21]. In addition to the provided mix designs, recommendations were made for developing other non-proprietary UHPC blends. The researchers recommended that the w/c ratio be kept between 0.2 to 0.3, that the aggregate to cement ratio be kept between 1.0 and 2.0, that fiber volume fraction be kept between 1% and 2%, that the weight of silica fume present equal 25% of the weight of cement, and that other supplementary cementitious materials be equal to 25% of the weight of cement [22].

## 2.2 UHPC in Accelerated Bridge Construction

UHPC has been used in accelerated bridge construction for more than 20 years. The first North American bridge built using UHPC and ABC technologies was a footbridge in Sherbrooke, Quebec, Canada in 1997 [23]. All structural elements on this bridge were made from precast UHPC and were fastened into place via prestressing.  Each element was also steam cured to provide compressive strengths in excess of 29,000 psi.

The first American bridge to incorporate UHPC was the Mars Hill Bridge, built in 2006 in Iowa [24]. This bridge used Ductal UHPC in its precast girders, reducing the weight and size of the structural members and eliminating the need for rebar stirrups for shear reinforcement. The success of UHPC as a structural material led to the FHWA's development of a precast girder and deck combination element known as the "pi-girder," which was later used for further construction on bridges in Iowa [25]. The design of the second-generation pi-girder is shown in Figure 2-1, and a field installation of the pi-girder is shown in Figure 2-2.

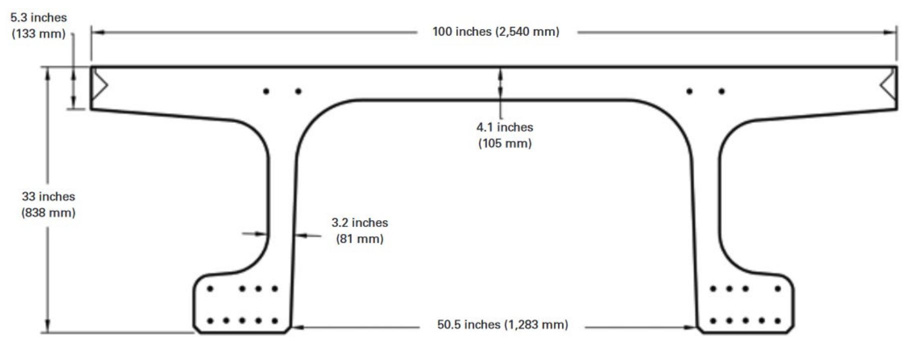



**Figure 2-1: 2nd Generation FHWA Pi-girder Cross Section**

**Figure 2-2: A worker guides a pi-beam into place in Buchanan County, Iowa [25]**

While the current cost of UHPC may prevent its widespread use for entire structural systems, the material has excellent capacity to secure other precast elements together. In this application, normal concrete precast elements are placed onsite and the UHPC is poured in the gaps between them in what is known as a closure pour. In this manner, precast deck panels can be fastened into one composite deck, and that composite deck can be fastened to the bridge girders through shear studs and keys [3, 26]. FHWA testing has found that these composite UHPC joints could eliminate the need for formwork and still meet AASHTO requirements [26]. This type of composite connection has been used to great effect in box beam bridges in Virginia [27] and Illinois [28].

## 2.3 Accelerated Bridge Construction in Georgia

Accelerated bridge construction and UHPC has been used on two projects to date in Georgia. The first structure in Georgia to incorporate UHPC was a bridge on State Road

211 over Beech Creek near Athens, GA. It consists of a single 148-foot span, with a 40-foot gutter-to-gutter width. Full depth precast deck panels 8.75 inches thick were used in place of a cast-in-place deck. The rebar overlap in the transverse and longitudinal joints was 5 inches. The bottom of the transverse joint was designed to fit snugly to reduce the amount of necessary formwork, while the top was given a 2-inch gap to allow for UHPC placement. Additionally, UHPC was utilized in the shear connections. The UHPC used on the project was Ductal UHPC provided by Lafarge. Aside from the first placement day, pours were done in the night in order to avoid hot placement temperatures [29]. A diagram of the joint details is given in Figure 2-3 and Figure 2-4. The use of UHPC in this project allowed for accelerated bridge construction, with the bridge opening back up to traffic after only 60 days of construction.

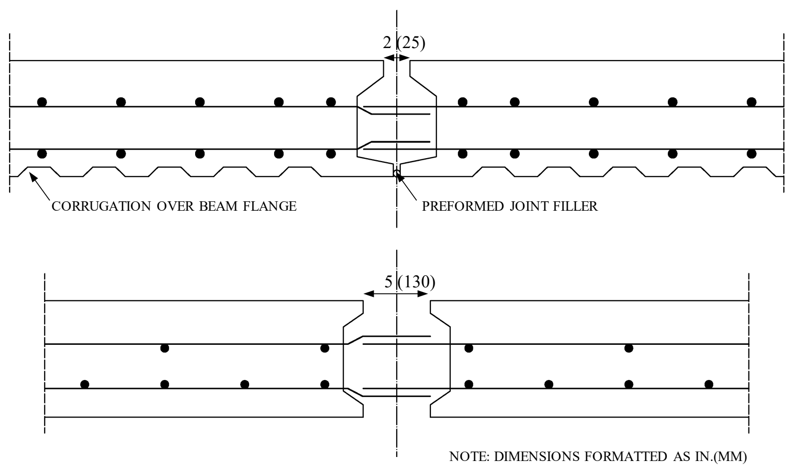



**Figure 2-3: Typical transverse [top] and longitudinal [bottom] joint details from SR 211 Bridge [30]**

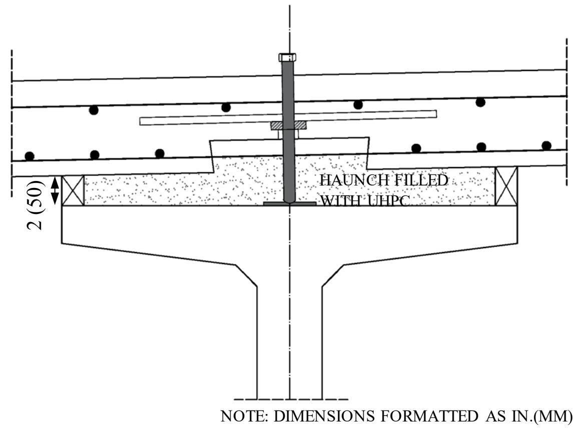



**Figure 2-4: Typical shear connection detail from SR 211 Bridge [30]**

The second bridge to be constructed with UHPC in Georgia was a bridge on County Road 131 in Henry County, Georgia. This bridge was constructed in the same manner as the previous State Road 211 bridge and all joint details were identical with the exception of the transverse joints. After experiencing difficulties with placing UHPC in the 2-inch top opening of joints on the State Road 211 bridge, the transverse joints on the County Road 131 bridge were expanded to 5 inches, as seen in Figure 2-5.

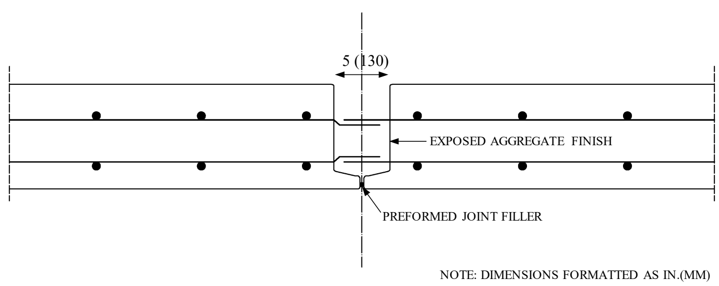



**Figure 2-5: Henry County / County Road 131 transverse joint details**


**Figure 2-6: Workers fill a transverse joint on the County Road 131 Bridge with UHPC**

## 2.4 The Suitability of Local Materials for UHPC

Georgia is home to two cement plants and 18 cement terminals [31], making cement easily accessible from all parts of the state. Georgia also has a wealth of aggregate sources and is supplied by all major admixture suppliers. While Georgia has ample cement and aggregate sources, it is lacking in easy access to silica fume, a common supplementary cementitious material (SCM) used in the production of UHPC.

Silica fume's high reactivity and ultra-fine particle size contribute to developing a dense concrete matrix, greatly improving both the compressive strength and durability of the concrete [32, 33]. While silica fume is the most common supplementary cementitious material used in UHPC, other ultrafine materials such as limestone, powdered silica, powdered phonolite, and metakaolin have been found to be suitable replacements for silica fume in providing improved density and compressive strength [34]. Of these materials, Georgia has both limestone and kaolinite in plentiful supply. Georgia's limestone deposits have been well-documented as far back as 1916 [35], but it is Georgia's kaolinite supply that sets it apart from other states. Georgia is one of the leading kaolinite-producing regions in the world [36]. The availability of metakaolin in Georgia makes it an attractive option as a replacement for silica fume, as it has been shown that metakaolin can perform as a suitable replacement for silica fume in UHPC [37, 38].

## 2.5 UHPC Mix Design Methods

The early development of UHPC mixes relied upon optimized particle packing to generate material blends with low porosity and high compressive strengths [16, 17]. The process of particle packing optimization increases the strength of the concrete by minimizing the amount of void space present in the material, filling the voids instead with additional aggregate or cementitious material. There are two methods of particle packing optimization that are commonly utilized: the Compressible Particle Model (CPM) and the Modified Andersen-Andreassen Model. In addition, mixes are commonly designed in a test-matrix approach, whereby one baseline mix is continuously trialed with one mix variable at a time being adjusted.

### *2.5.1 The Compressible Particle Model*

The CPM was developed by Francois de Larrard in 1999 [39]. This method uses the particle size distribution of its component particles (both reactive and nonreactive) alongside their virtual packing densities to calculate a compaction index, *K.* Additionally, this model considers both the wall effect, the perterbation that walls cause to the dispersion of particles, and the loosening effect, whereby smaller particles wedge larger particles apart and decrease their packing coefficient [39]. The Compressible Particle Model has been shown to perform well for large, easily-measureable particles such as aggregates, but it is very sensitive to the particle size distributions in finer materials like cement [40].

To calculate the packing index *K*, users of the CPM must first calculate the maximum theoretical packing density of each particle size, $\gamma$. In order to do this, the user must also know each particle's maximum possible packing density, $\beta$, the volumetric proportion of each particle size, $y$, and the loosening coefficient and wall coefficients, $a_{ij}$ and $b_{ji}$. The loosening coeffecient is calculted via Equation 2.1, while the wall effect coefficient is calculated via Equation 2.2. These values are then used in Equation 2.3 to calculate $\gamma$.

$$a_{ij} = \sqrt{1 - \left(1 - \frac{d_j}{d_i}\right)^{1.02}} \tag{2.1}$$

$$b_{ji} = 1 - \left(1 - \frac{d_i}{d_j}\right)^{1.5} \tag{2.2}$$

$$\gamma_i = \frac{\beta_i}{1 - \sum_{j=1}^{i-1}\left[1 - \beta_i + b_{ij}\beta_i\left(1 - \frac{1}{\beta_j}\right)\right]y_j - \sum_{j=i+1}^{n}\left[1 - \frac{a_{ij}\beta_i}{\beta_j}\right]y_j} \tag{2.3}$$

Upon solving for $\gamma_i$, the value *K* can be found as the sum of all of the partial packing densities, as shown in Equation 2.4. In this equation, $\Phi$ is the actual packing density of the whole concrete mixture. For a self-consolidating concrete, de Larrard recommends that $K = 4$ [39].

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{y_i/\beta_i}{1/\Phi - 1/\gamma_i} \tag{2.4}$$

The CPM assumes that all particles are spherical in shape, that wall interactions only occur against smooth, flat walls, and that the intrusion of fibers can be ignored due to their relatively short length [39].The maximum packing density, $\beta$, is determined using a variety of experimental methods to find the maximum measured packing density, then back-calculating the virtual packing density using a correction factor [39, 41]. Some of these experimental methods can be overly-harsh towards soft grains like limestone (a common filler material in UHPC) because they crush the grains into a finer powder, providing inaccurate results [42]. In his own paper on using the CPM for mix design, de Larrard provides no clarification on how to consider the virtual packing density [43].

### *2.5.2 The Modified Andersen and Andreasen Model*

The original Andersen and Andreasen model was first published in 1930, and involves using a target function based on an infinite distribution of particle sizes [44]. Because there must be finite size limits, Funk and Dinger modified the model to include a minimum particle diameter. The modified equation is shown in Equation 2.5, where *P(D)* is the fraction of total solids smaller than diameter *D*, and *q* the distribution modulus. [45] This equation generates an "ideal" gradation curve when presented graphically, which mix designs can be visually adjusted to match.

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \tag{2.5}$$

The variable $q$ is not a fixed or measurable variable, but instead is a variable to be adjusted until the particle size distribution curve of the selected materials is as close as possible to an "ideal" particle size distribution. It has been found that the optimal packing density for a mixture that is flowable and self-consolidating can be obtained by using a value of $q$ between 0.22 and 0.25 [46-48].

### *2.5.3 Test Matrix Mix Design*

Test matrix-based mix design has been used extensively to design non-proprietary mixes in Arkansas [6], Colorado [7], Michigan [8], Montana [9], and South Carolina [10], and for other geographic regions around the United States [21]. This procedure requires less calculations than using a particle packing model, but requires much more experimental work and a greater expenditure of materials. Published papers that have utilized a matrix-based frequently include sections addressing particle packing in the cement paste, but correlate the higher particle packing with increased workability in measures such as the ASTM C1611 spread test [21]. In a typical UHPC test matrix design, the first step is establishing a baseline mortar mix. The baseline mix can either be based off of a previous successful mix design from literature, or a new mortar can be developed. Once a baseline has been established, each component of the mix design is then tested for compressive strength and for workability via flow table testing. These components are then weighted against the objectives of the mix designer to determine if the mix is successful.

# CHAPTER 3. LABORATORY-SCALE MIX DESIGN

## 3.1 Background and Procedure

### *3.1.1 Mix Design Process*

A dual approach for the mix design process was considered in order to find a workable mix and determine the degree to which it could be improved though particle packing. First a parametric approach was taken to develop UHPC mixes that met performance criteria for workability and strength. The process followed is outlined in Figure 3-1. This approach built upon published non-proprietary UHPC mixes, substituting locally available materials to minimize cost. The approach first identified appropriate water-to-binder ratios (w/b) and then adjusted the superplasticizer content to achieve desired flow. This initial identified mixture is then used as a baseline mixture, with subsequent mixes changing one mix design variable at a time to observe the effects of the change. Upon completion of the test matrix approach, the final mix was evaluated for further optimization using particle packing.

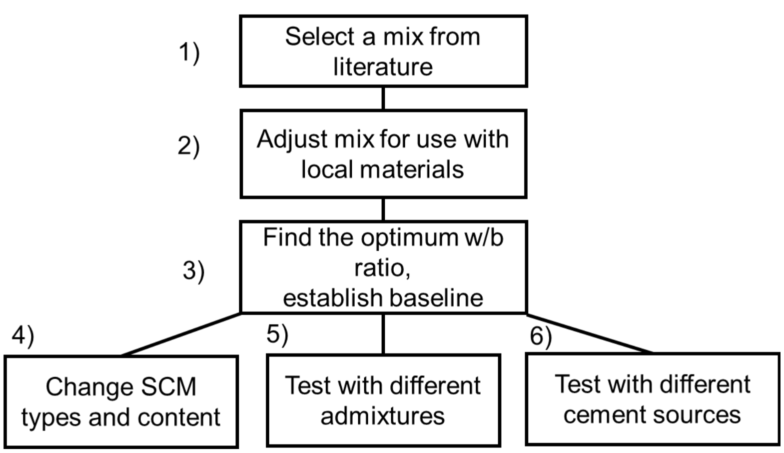



**Figure 3-1: Testing order for the parametric approach**

Each trial mix was evaluated on the basis of compressive strength and workability. Compressive strength was evaluated by means of ASTM C109 and workability was evaluated via the ASTM C1437 flow table test. The compressive strength targets for the mix were 14,000 psi compressive strength at 3 days and 18,000 psi compressive strength at 28 days. The 14,000 psi target was chosen because it is the strength at which FHWA guidelines allow the development length of reinforcement to be taken as 8 bar diameters [3]. A mix that reaches 14,000 psi compressive strength quickly will enable construction to proceed at a more rapid pace. Compression testing specimens are shown in Figure 3-2. The 2-inch by 2-inch cube molds were used because they are the ASTM standard for testing mortars, which UHPC can be considered as due to the absence of coarse aggregates in the mix. Fibers were not included in these specimens because their contribution to compressive strength is marginal [49] and because steel fibers were temporarily unavailable due to the effects of steel tariffs.

**Figure 3-2: Mortar cube specimens being cast for compression testing**

Due to the tight spaces and narrow joint widths, UHPC must be self-consolidating when used as a joint filler in ABC construction. No matter which materials are included in UHPC, it will be expected to be self-consolidating. For this reason, every mix was adjusted via the addition of superplasticizer until it reached a 9-inch-diameter flow on the ASTM C1437 test, plus or minus one half inch. The process by which these superplasticizer adjustments were made is detailed in Section 3.1.3. The 9-inch target was chosen because it would allow for self-consolidating behavior upon the addition of workability-reducing steel fibers in the large-scale trials [50].

**Figure 3-3: Measuring the flow of a mixture on the flow table**

Following the test matrix approach, the software EMMA was used to conduct a particle packing optimization. Particle packing optimization eliminates void space in the concrete, creating a denser material with higher compressive strength. This optimization was done with the same materials used in the test-matrix trials. The software used for this optimization uses the modified Andersen and Andreasen model to evaluate the particle packing of the mix design [51]. It was chosen for this process because it could easily and quickly evaluate a single mix, in a simple graphical interface, as opposed to the Compressible Particle Method, which requires complicated math and comprehensive testing to be done on each particle size used in the mix. The simplicity and ease of use of the modified Andersen and Andreasen approach made it ideal for optimizing a single mix.

### *3.1.2 Materials*

Three commercially produced cements readily available in Georgia were selected for testing: Holcim ASTM C150 Types I (Holcim; Duluth, Georgia), I/II (Argos; Atlanta, Georgia), and Type III (Argos; Atlanta, Georgia). The Bogue composition and Blaine fineness of these cements, provided by the manufacturer, are shown in Table 3-1. These cements were chosen due to their low cost and widespread availability. The Type I cement was ordered as a baseline because of its relatively high $C_3S$ content. The Type I/II and Type III cements were included to evaluate the effects of decreasing the $C_3S$ content and the effects of increasing fineness, respectively.

Both ASTM C618 class C and class F fly ash were obtained locally (Boral Resources, Taylorsville, GA). Metakaolin (BASF Metamax, McIntyre, GA) was selected for testing due to its high purity and small particle size. This central location would serve to make it easily available throughout the state. This material is viewed as a potential substitute for silica fume, which is more commonly used in UHPC but is not produced in Georgia.

**Table 3-1: Cement Composition**

| Cement ID: | **Holcim Type I** | **Argos Type I/II** | **Argos Type III** |
|---|---|---|---|
| $C_2S$ (%) | 18 | 18 | 17 |
| $C_3S$ (%) | 58 | 52 | 53 |
| $C_3A$ (%) | 2 | 6 | 7 |
| $C_4AF$ (%) | 13 | 9 | 10 |
| $SiO_2$ (%) | 20.5 | 20.1 | 20.4 |
| $Al_2O_3$ (%) | 4.4 | 4.4 | 4.9 |
| $Fe_2O_3$ (%) | 3.1 | 3.1 | 3.4 |
| CaO (%) | 64.1 | 62.7 | 63.6 |
| MgO (%) | 2.5 | 2.9 | 1.3 |
| $SO_3$ (%) | 3.3 | 3.1 | 3.6 |
| $CO_2$ (%) | 2 | 1.9 | 1.9 |
| Limestone (%) | 2.5 | 2.6 | 0 |
| NaEq (%) | 0.40 | 0.34 | 0.46 |
| Loss on Ignition (%) | 2.0 | 2.8 | 1.9 |
| Blaine Fineness ($m^2$/kg) | 394 | 394 | 538 |
| Specific Gravity | 3.10 | 3.16 | 3.15 |

One type of masonry sand (South Georgia Sand; Bainbridge, Georgia) was selected for initial testing. Masonry sand was selected because of its fineness and because fine sands are generally used for UHPC. This masonry sand is alluvial, and gradation data for it is shown in Table 3-2 and Figure 3-4.

Two widely available commercial superplasticizers were evaluated: Sika ViscoCrete 2100 and BASF MasterGlenium 7920. Both admixtures are polycarboxylate ether high-range water reducers conforming to ASTM C494 requirements. Additionally, an accelerator (BASF MasterSet AC 534) was used in some mixes. These admixtures are all widely available and easily obtained in Georgia.

**Table 3-2: Masonry Sand Gradation Data**

| Sieve Size | Masonry Sand |
|---|---|
| | Percent Passing (%) |
| #4 | 100 |
| #8 | 99.99 |
| #16 | 95.08 |
| #30 | 63.98 |
| #50 | 17.99 |
| #100 | 1.53 |
| #200 | 0.29 |
| **Fineness Modulus** | **2.21** |
| **Specific Gravity (ASTM C128)** | **2.65** |
| **Absorption Capacity (%) (ASTM C128)** | **0.93** |

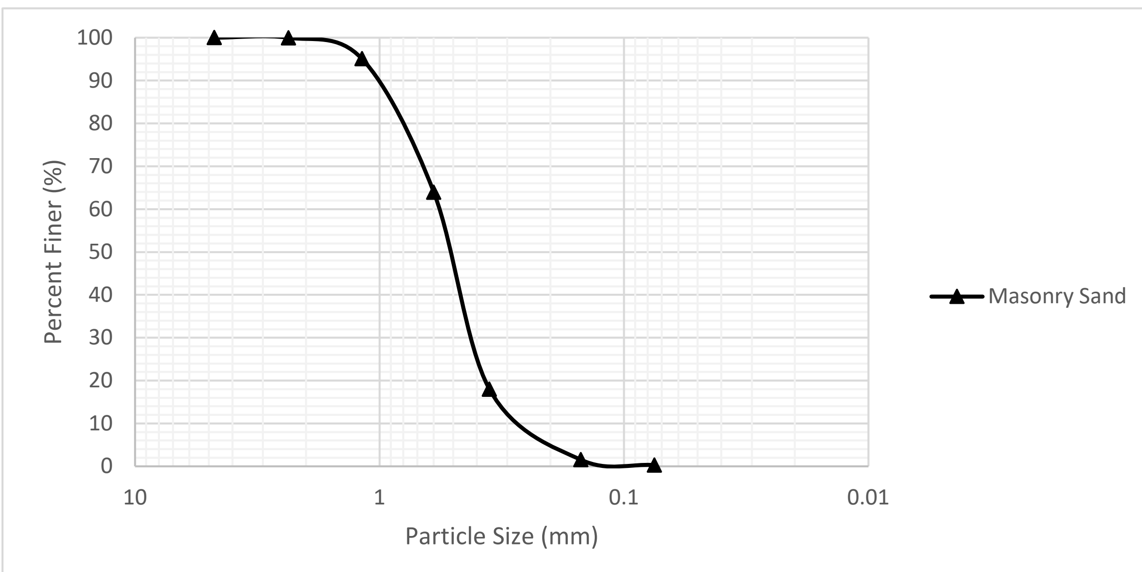



**Figure 3-4: Masonry Sand Gradation Curve**

### *3.1.3 Mixing Procedure*

To conserve materials and aid in the ease of mixing, initial mixing was performed in 0.05 $ft^3$ batches. A 10-quart (0.33 $ft^3$) benchtop planetary mixer (Hobart) with a paddle blade was used to mix all mixture components. The following mixing procedure was adapted from several papers on UHPC mix development [9, 49, 52].

1. Mix oven-dry sand and SCMs on low speed for 2 minutes
2. Add cement and mix on low for 1 minute
3. Add water over the course of 30 seconds and mix on low for a further 30 seconds
4. Add superplasticizer and mix on low for ten minutes
5. Test the material's flow
6. Cast specimens

If further flow was needed after step 5, superplasticizer was added in 2 mL doses and mixed for a further 2 minutes per dose until the mix reached 9 inches of flow. The mix would then be re-mixed following the above procedure with the adjusted amount of superplasticizer. This method allows for all mixes to be evaluated with the same mixing time. Superplasticizer was added after the water because it has been observed that delaying the addition of superplasticizer increases the fluidity of self-consolidating concrete and UHPC [53, 54].

### *3.1.4 Casting and Testing Procedures*

Nine 2-inch by 2-inch by 2-inch cubic specimens were cast for each mix. UHPC was allowed to flow into each mold until the mold was slightly over-filled, then the mold was struck five times with a mallet to drive out any air bubbles. The specimens were then trowelled down to the height of the mold, covered with plastic to prevent the escape of moisture, and allowed to set for 24 hours. After being removed from the molds the specimens were labelled and left to cure in a 73° F bath of water saturated with lime. Specimens were tested for compressive strength at 3, 7, and 28-day intervals, with three specimens being tested at each age. The cubes were loaded at a rate of 18,000 pounds per minute until failure.

### 3.2 Approach to Mix Development

The process of designing the mix followed a test-matrix based approach coupled with a particle packing analysis. First, a baseline mixture was established by adapting a mix from literature. Then this baseline mix was adjusted one component at a time to determine what effects the changed component would have on compressive strength, workability, or both.

As a starting point for the mix design, the general UHPC-4 mixture from the 2013 FHWA Tech Note *Development of Non-Proprietary Ultra-high Performance Concrete for Use in the Highway Bridge Sector* [21] was selected for adjustment. This mix was chosen because this UHPC was presented as being adaptable to materials found throughout the United States and was one of few that incorporated fly ash over other materials not found in Georgia, such as silica flour.

The UHPC-4 mix incorporates silica fume. Therefore, the first adaptation was to replace silica fume with metakaolin 1:1 by weight. Additionally, regular Portland cement was used in place of white Portland as an availability and cost-saving measure. This mix design is shown in Table 3-3.

**Table 3-3: The UHPC Mix Used as a Design Starting Point**

| UHPC-4 (Q; United States) [21] | |
|---|---|
| **Material** | **Quantity** |
| White Portland Cement | 1248 lb/yd$^3$ |
| Class F Fly Ash | 303 lb/yd$^3$ |
| Silica Fume | 312 lb/yd$^3$ |
| Masonry Sand | 1871 lb/yd$^3$ |
| Superplasticizer | 45 lb/yd$^3$ |
| Water/Binder: 0.154 | |

To begin our adjustments, silica fume was replaced with a 1:1 weight ratio with metakaolin, as seen in Table 3-4. This mix design was attempted twice, but neither attempt was successful in developing a cohesive mixture. Large agglomerations of metakaolin were observed in both mixes, and despite the addition of superplasticizer the cement and aggregates remained very dry and crumbly. The mixture was reapportioned to reduce the metakaolin content and to increase sand and fly ash, due to their lower cost and potential to improve workability. Additional water was also added for workability purposes. The adjusted mix is shown in Table 3-5. This mix proved to be workable, so testing proceeded to identify which w/b ratio would be set as the baseline value for use in following tests.

**Table 3-4: 1:1 Replacement of Silica Fume with Metakaolin**

| **Material** | **Quantity** |
|---|---|
| Type I Portland Cement | 1248 lb/yd$^3$ |
| Class F Fly Ash | 303 lb/yd$^3$ |
| Metakaolin | 312 lb/yd$^3$ |
| Masonry Sand | 1871 lb/yd$^3$ |
| Superplasticizer | 45 lb/yd$^3$ |
| Water/Binder: 0.154 | |

**Table 3-5: Adjusted Mix with Reduced Metakaolin**

| Material | Quantity |
|---|---|
| Type I Portland Cement | 1248 lb/yd$^3$ |
| Class F Fly Ash | 387 lb/yd$^3$ |
| Metakaolin | 100 lb/yd$^3$ |
| Masonry Sand | 1997 lb/yd$^3$ |
| Superplasticizer | 45 lb/yd$^3$ |
| Water/Binder: 0.25 | |

### *3.2.1 Water to Binder Ratio*

The mix in Table 3-5 was tested at w/b ratios of 0.14, 0.18, 0.25, and 0.30 to determine which w/b ratio would provide the highest strength. These w/b ratios were chosen to represent the wide range of w/b ratios that are commonly reported in UHPC literature. These mixes and their corresponding superplasticizer dosage are given in Table 3-6. It was found that the 0.18 w/b ratio provided the highest strengths of the w/b ratios tested. From this, the baseline mix "GT Baseline" was established, as shown in Table 3-7, and used for all future tests.

**Table 3-6: W/B Ratio Trial Mixes**

| Material | Quantity | | | |
|---|---|---|---|---|
| | **0.14 W/B** | **0.18 W/B** | **0.25 W/B** | **0.30 W/B** |
| Type I Portland Cement | 1248 lb/yd$^3$ | 1248 lb/yd$^3$ | 1248 lb/yd$^3$ | 1248 lb/yd$^3$ |
| Class F Fly Ash | 387 lb/yd$^3$ | 387 lb/yd$^3$ | 387 lb/yd$^3$ | 387 lb/yd$^3$ |
| Metakaolin | 100 lb/yd$^3$ | 100 lb/yd$^3$ | 100 lb/yd$^3$ | 100 lb/yd$^3$ |
| Masonry Sand | 1997 lb/yd$^3$ | 1997 lb/yd$^3$ | 1997 lb/yd$^3$ | 1997 lb/yd$^3$ |
| Superplasticizer (BASF 7920) | 13.5 L/yd$^3$ | 8.64 L/yd$^3$ | 2.70 L/yd$^3$ | 1.62 L/yd$^3$ |
| Water/Binder | 0.14 | 0.20 | 0.25 | 0.30 |

**Table 3-7: GT Baseline Mix**

| Material | Quantity |
|---|---|
| Type I Portland Cement | 1248 $lb/yd^3$ |
| Class F Fly Ash | 387 $lb/yd^3$ |
| Metakaolin | 100 $lb/yd^3$ |
| Masonry Sand | 1997 $lb/yd^3$ |
| Superplasticizer (BASF 7920) | 8.64 $L/yd^3$ |
| Water/Binder: 0.18 | |

### *3.2.2 Supplementary Cementitious Material Content and Type*

Following the water/binder trials, the supplementary cementitious material contents in the mix were adjusted to determine their effects on compressive strength. Class C fly ash was substituted 1:1 by weight with class F fly ash in the GT Baseline mixture. This mix was given the name “FA (C)”. Additionally, two mixes containing 8% and 10%, with metakaolin replacing less-reactive fly ash, were attempted. Besides the changes in SCM content, all other design variables were held constant. These mixes were called “8MK” and “10MK”, respectively. These mix designs are shown in Table 3-8.

**Table 3-8: Alternative SCM Composition Mix Designs**

| Material | Quantity | | |
|---|---|---|---|
| | *FA (C)* | *8MK* | *10MK* |
| Type I Portland Cement | 1248 $lb/yd^3$ | 1248 $lb/yd^3$ | 1248 $lb/yd^3$ |
| Fly Ash (class) | 387 (C) $lb/yd^3$ | 348 (F) $lb/yd^3$ | 313.2 (F) $lb/yd^3$ |
| Metakaolin | 100 $lb/yd^3$ | 139 $lb/yd^3$ | 173.5 $lb/yd^3$ |
| Masonry Sand | 1997 $lb/yd^3$ | 1997 $lb/yd^3$ | 1997 $lb/yd^3$ |
| Superplasticizer (BASF 7920) | 8.64 $L/yd^3$ | 9.72 $L/yd^3$ | 10.8 $L/yd^3$ |
| Water/Binder: 0.18 | | | |

### 3.2.3 *Effects of Admixtures*

The effects of using a different superplasticizer were also examined, with Sika 2100 being evaluated as a replacement for the BASF MasterGlenium 7920 used in the GT Baseline mix. This mix was given the name “SP2”. Further trials tested the effects that the addition of 20 ounces per hundred weight of cement (oz/cwt), called ACC-20 and 40 oz/cwt of accelerating admixture had on the compressive strength development of the mix. These mixes were referred to as “ACC-20” and “ACC-40,” respectively. The mix designs and admixture dosages are shown in Table 3-9.

**Table 3-9: Admixture Trial Mixes**

| **Material** | **Quantity** | | |
|---|---|---|---|
| | *SP2* | *ACC-20* | *ACC-40* |
| Type I Portland Cement | 1248 lb/yd$^3$ | 1248 lb/yd$^3$ | 1248 lb/yd$^3$ |
| Fly Ash (Class F) | 387 lb/yd$^3$ | 387 lb/yd$^3$ | 387 lb/yd$^3$ |
| Metakaolin | 100 lb/yd$^3$ | 100 lb/yd$^3$ | 100 lb/yd$^3$ |
| Masonry Sand | 1997 lb/yd$^3$ | 1997 lb/yd$^3$ | 1997 lb/yd$^3$ |
| Superplasticizer | 8.64 L/yd$^3$ (SIKA 2100) | 8.64 L/yd$^3$ (BASF 7920) | 8.64 L/yd$^3$ (BASF 7920) |
| Accelerator (BASF Masterset 534) | --- | 10.26 L/yd$^3$ | 20.52 L/yd$^3$ |
| Water/Binder: 0.18 | | | |

### 3.2.4 *Changing Cement Sources*

Finally, the cement source was varied to determine its effect on the strength and flowability. The Type I cement used in the GT Baseline had a higher $C_3S$ content than the alternative Type I/II trialed, providing insight into how $C_3S$ content affects strength development. The Type I/II and Type III versions are practically identical save for their Blaine fineness, providing insight into the effects of fineness on strength development.

**Table 3-10: Alternative Cement Mix Designs**

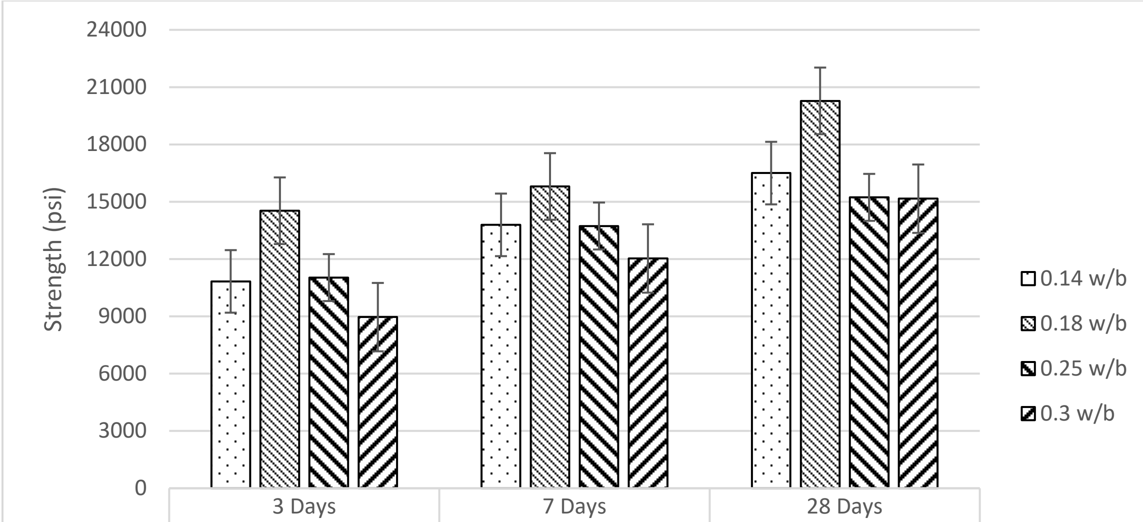
| **Material** | **Quantity** | |
|---|---|---|
| | **BL I/II** | **BL III** |
| Portland Cement | 1248 lb/yd$^3$ (Type I/II) | 1248 lb/yd$^3$ (Type III) |
| Class F Fly Ash | 387 lb/yd$^3$ | 387 lb/yd$^3$ |
| Metakaolin | 100 lb/yd$^3$ | 100 lb/yd$^3$ |
| Masonry Sand | 1997 lb/yd$^3$ | 1997 lb/yd$^3$ |
| Superplasticizer (BASF 7920) | 8.64 L/yd$^3$ | 8.64 L/yd$^3$ |
| Water/Binder: 0.18 | | |

## 3.3 Results

The following subsections present the results from the compression tests on each component that was evaluated.

### *3.3.1 Compressive Strength Development*

Figure 3-5 shows the influence of w/b on strength development over time. A 0.18 w/b ratio (0.25 w/c ratio) was the only mix to surpass the 18,000 psi compressive strength target. It is believed that the 0.14 w/b mix (0.2 w/c) had its early strength hampered by the excessive amount of superplasticizer necessary to achieve workability.

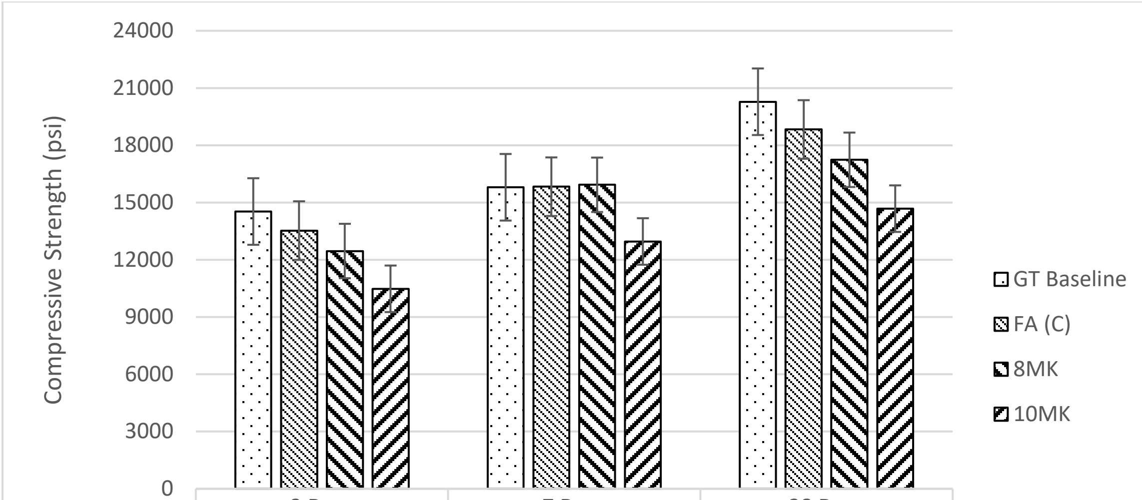



| | 3 Days | 7 Days | 28 Days |
|---|---|---|---|
| 0.14 w/b | 10830 | 13790 | 16500 |
| 0.18 w/b | 14530 | 15800 | 20280 |
| 0.25 w/b | 11030 | 13730 | 15230 |
| 0.3 w/b | 8960 | 12030 | 15160 |

**Figure 3-5: Effects of Adjusting W/B Ratio**

An interesting result, however, is that despite lower 3- and 7-day strengths, the 0.3 w/b mix achieved the same 28-day strength as the 0.25 w/b mix. Because fly ash reacts more slowly than metakaolin [55, 56], this late-age strength gain is likely due to later pozzolanic reaction of the fly ash. It can be inferred, then, that at these very low w/b ratios there is a proportion of fly ash that is unreacted and instead serves as an inert filler material.

To compensate for the presence of unreacted fly ash, two mixes increasing the level of metakaolin were mixed and tested. Mixes 8MK and 10MK incorporated 8% and 10% metakaolin by weight, respectively. Additionally, class C fly ash, which reacts both hydraulically and pozzolanically, was used in an attempt to improve late-age strength. The results of these tests are shown in Figure 3-6.




| | 3 Days | 7 Days | 28 Days |
|---|---|---|---|
| GT Baseline | 14530 | 15800 | 20282 |
| FA (C) | 13530 | 15830 | 18830 |
| 8MK | 12460 | 15930 | 17240 |
| 10MK | 10480 | 12960 | 14680 |

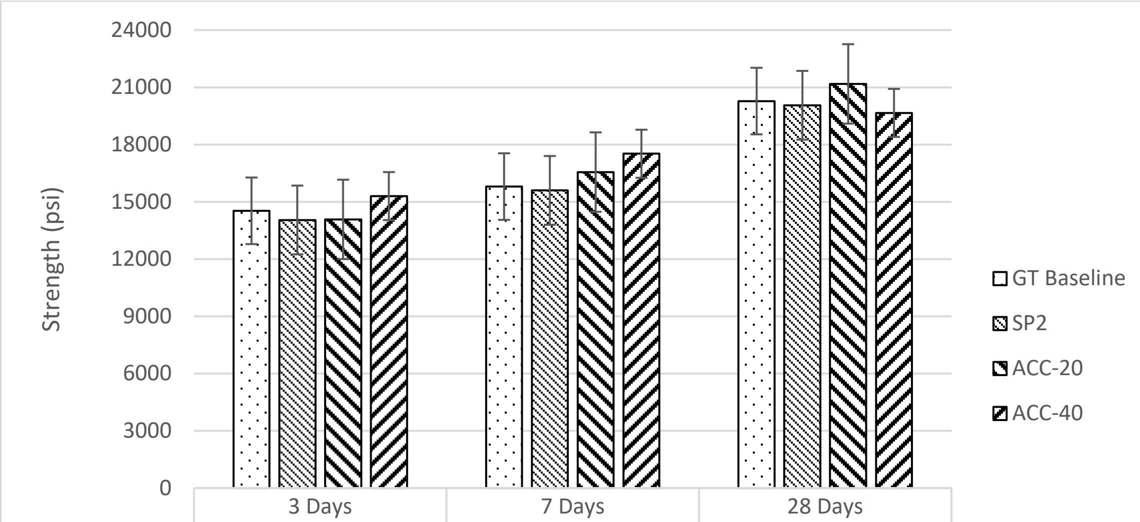
**Figure 3-6: Effects of Adjusting SCM Content**

From the figure, it can be seen that the 1:1 replacement of class F fly ash with class C fly ash is the only adjustment that still exceeds the 18,000 psi strength target. Strengths decreased as the amount of metakaolin in the mix increased. Additionally, expansion of the concrete was observed in the 8% and 10% metakaolin mixes, as shown in Figure 3-7 where the concrete can be seen bulging above the molds after setting. This type of expansion could be an issue in accelerated bridge construction where precast members could be pushed out of place by expanding concrete.

**Figure 3-7: Mix 10MK showing expansion above the molds**

The effect of different admixtures was compared to examine sensitivity of the GT Baseline mix to alternative admixtures. Both superplasticizers examined produced virtually identical strengths at the similar dosage levels. Since both are based on polycarboxylate ether chemistry, the similar behavior is expected. However, manufacturers have different proprietary admixture compositions, with the superplasticizer used in GT Baseline having a 33% solids content while the superplasticizer in SP2 contains 40% solids. The similarity in dosages between these two is encouraging, as it suggests that UHPC can be produced rather robustly using a variety of materials suppliers.

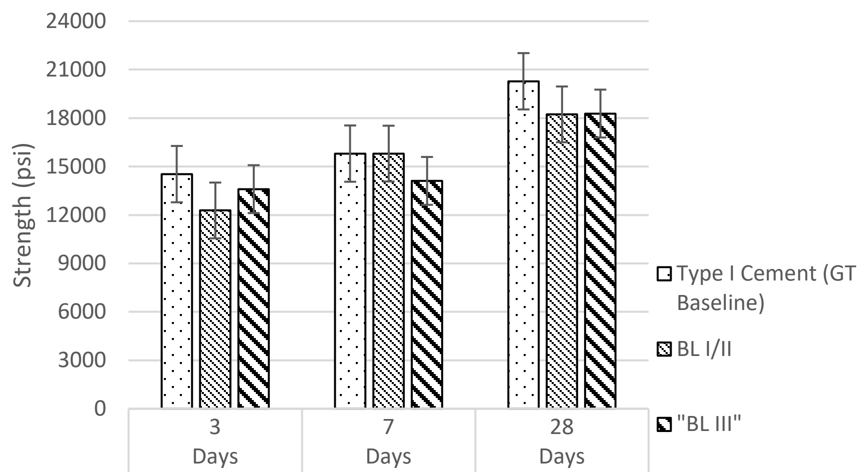
Additionally, two dosages of accelerator were tested to observe their effects on the compressive strength. BASF MasterSet AC was added in 20 oz/cwt and 40 oz/cwt dosages as per the manufacturer’s recommendation for moderate and high dosages. Mix ACC-20 corresponds to the 20 oz/cwt dosage, whereas ACC-40 corresponds to the 40 oz/cwt dosage. While the higher dosage of accelerator provided higher early-age strength, the lower dosage of accelerator proved better at long-term strength gain. These results are shown in Figure 3-8.




| | 3 Days | 7 Days | 28 Days |
|---|---|---|---|
| GT Baseline | 14530 | 15800 | 20280 |
| SP2 | 14050 | 15600 | 20060 |
| ACC-20 | 14080 | 16560 | 21180 |
| ACC-40 | 15300 | 17520 | 19660 |

**Figure 3-8: Effects of Admixture Substitution**

Finally, three cement sources were compared. Mix BL I/II is the GT Baseline mix with Type I/II cement, while BL III is the GT Baseline mix with Type III cement. It was found that the mix would exceed 18,000 psi compressive strength objective with any of the chosen cements. The 3-day strength of the Type I/II and Type III mixes was reduced compared to the GT Baseline. Although the 7-Day strength for both the Type I/II and Type I was equal, the Type I performed better across the full range of days. This can be attributed to the higher $C_3S$ content of the Type I cement. The Type III cement exhibited higher 3-day strength than the chemically similar Type I/II, demonstrating the effects of cement fineness on early-age strength. These results are shown in Figure 3-9.




| | 3 Days | 7 Days | 28 Days |
|---|---|---|---|
| Type I Cement (GT Baseline) | 14530 | 15800 | 20280 |
| BL I/II | 12280 | 15800 | 18230 |
| "BL III" | 13600 | 14110 | 18280 |

**Figure 3-9: Effects of Cement Type and Composition**

## 3.4 Particle Packing Optimization

Following the test matrix approach, the GT Baseline mix was optimized via the modified Andersen and Andreasen model developed by Funk and Dinger. First, the particle size distribution of every cement and supplementary cementitious material was acquired through the use of a laser size analyzer. Gradations for the two sands were obtained through a sieve analysis. The gradation information was imported into EMMA, a software available for free through ELKEM Silica. The baseline mix design was entered, and a distribution modulus, *q*, value was selected to generate the ideal distribution curve. For this optimization, a *q* value of 0.25 was selected, based upon literature [46, 47]. The baseline mix design was compared with the ideal distribution curve. This result is shown in Figure 3-10, where the red curve represents an ideal distribution and the blue line is the unchanged distribution of the baseline mix.

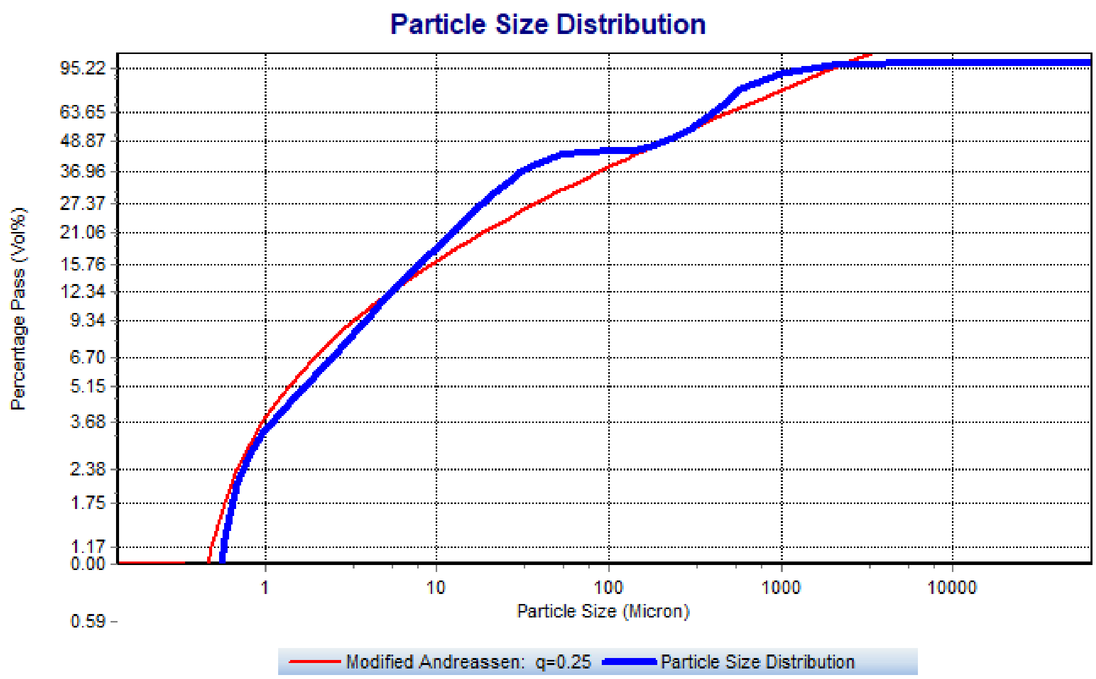



**Figure 3-10: Particle Size Distribution of the GT Baseline Mix**

The modified Andersen and Andreasen model is an iterative approach, and requires adjustments to be made until the mix's particle size distribution matches the ideal packing curve. After many adjustments, the mix in Table 3-11 was found to best represent the ideal packing curve. Alongside the optimized mix shown in Table 3-11, the GT Baseline mix is included for comparison. The particle size distribution for the optimized mix is shown in Figure 3-11.

Over the course of testing, however, the optimized mix had design issues that prevented its consideration as a potential UHPC mix. The mix was attempted at w/b ratios ranging from 0.15 to 0.25, the common range of UHPC w/b ratios, and even up to a 0.30 w/b ratio. In all of these cases, workability was very poor and required the addition of superplasticizer to a level that prevented the samples from setting. Because the concrete never set, compression tests were unable to be performed. Further experiments with this mix were discontinued.

**Table 3-11: The Particle Packing Optimized Baseline Mix**

| Material | Quantity | |
|---|---|---|
| | *Optimized Mix* | *GT Baseline* |
| Type III Portland Cement | 826.5 lb/yd$^3$ | 1248 lb/yd$^3$ |
| Class F Fly Ash | 357.9 lb/yd$^3$ | 387 lb/yd$^3$ |
| Metakaolin | 165.7 lb/yd$^3$ | 100 lb/yd$^3$ |
| Masonry Sand | 2381.6 lb/yd$^3$ | 1997 lb/yd$^3$ |
| Superplasticizer | Determined during testing | 8.64 L/yd$^3$ |
| Water/Binder: 0.18 | | |

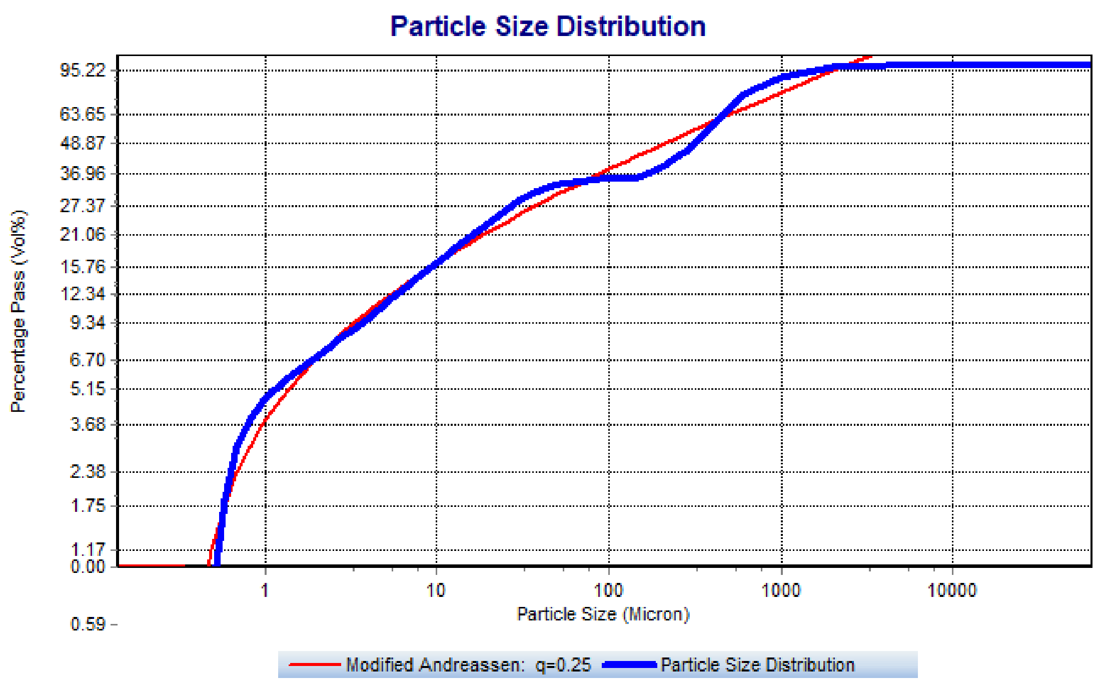



**Figure 3-11: Particle Size Distribution of the Optimized Baseline Mix**

### 3.5 Mix Design Price Estimate

In order to gauge the cost-effectiveness of each mix that achieved higher than 18,000 psi strength, the commercial price of each mix ingredient was acquired from the producers. These component prices are shown in Table 3-12. Based on these cost estimates, we can determine the cost estimate for each of these mixes, as given in Table 3-13. Although they were not mixed in this trial, the cost of steel fibers is also included for consideration, with the price of steel fibers being based on inclusion of 2% steel fibers by volume.

**Table 3-12: Component Prices for Price Estimation**

| Material | Price |
|---|---|
| Type I Portland Cement | $130 per ton |
| Fly Ash (both F and C) | $50 per ton |
| Metakaolin | $600 per ton |
| Masonry Sand | $15 per ton |
| Superplasticizer (both varieties) | $13 per gallon |
| Accelerator | $7 per gallon |
| Steel Fibers | $4,000 per ton |

**Table 3-13: Mix Price Estimates for Top-performing Mixes**

| Material | Price Per Cubic Yard | | |
|---|---|---|---|
| | *GT Baseline* | *ACC-20* | *ACC-40* |
| Portland Cement | $81.12 | $81.12 | $81.12 |
| Fly Ash (Class F) | $9.67 | $9.67 | $9.67 |
| Metakaolin | $29.94 | $29.94 | $29.94 |
| Masonry Sand | $14.98 | $14.98 | $14.98 |
| Superplasticizer | $29.67 | $29.67 | $29.67 |
| Accelerator | $0 | $18.97 | $37.94 |
| **Pre-fiber Total:** | **$165.38** | **$184.35** | **$203.32** |
| Steel Fibers | $529.03 | $529.03 | $529.03 |
| **Total Price:** | **$694.41** | **$713.38** | **$732.35** |

The GT Baseline, ACC-20, and ACC-40 mixes were selected because they were the highest performing mixes for each component's price. For example, although the Type I/II and Type III cements also reached 18,000 psi, the regular Type I used in the GT Baseline mix presented superior performance at the same price. Similarly, the FA (C) mix also reached 18,000 psi compressive strength, but is outperformed at that price point by the class F ash in the GT Baseline mix.

It can be seen that steel fibers are overwhelmingly the controlling factor in determining the price of the mix design. If the price of each mix is divided by its 28-day compressive strength, we see that the GT Baseline mix costs $34.24 per ksi, ACC-20 costs $33.68 per ksi, and ACC-40 costs $37.25 per ksi. By this metric, the GT Baseline performs nearly as well as the ACC-20 on a cost-per-ksi basis and is overall cheaper per cubic yard. The GT Baseline also has a slightly simpler mixing process because it requires one less admixture.

## 3.6 Conclusions

The GT Baseline mix performed the best out of all mixes considered. This mix is self-consolidating, is cost effective at $694 per cubic yard, and is produced entirely from local materials, and exceeds the 18,000 psi compressive strength requirement. It does also not require expensive accelerators or specialty mixing equipment. For future work, this mix will be referred to as GT UHPC and is shown in Table 3-14. If a project requires a guarantee of higher early strengths, it has also been shown that the addition of 10.26 liters per cubic yard of accelerating admixture may be added to the mixer for little additional cost.

**Table 3-14: GT UHPC Mix Design**

| Material | Quantity |
|---|---|
| Type I Portland Cement | 1,248 $lb/yd^3$ |
| Class F Fly Ash | 387 $lb/yd^3$ |
| Metakaolin | 100 $lb/yd^3$ |
| Masonry Sand | 1,997 $lb/yd^3$ |
| Superplasticizer (BASF 7920) | 320 $mL/ft^3$ |
| Water/Binder: 0.18 | |

Additionally, it was observed that:

- Some portion of fly ash remains unreacted in the mix, as can be seen by the w/b targeting trials. The replacement of fly ash with additional metakaolin should be avoided, however, due to issues with expansion that occur at higher metakaolin replacement levels.
- The addition of accelerating admixtures can provide strengths in excess of 21,000 psi, but higher dosages of accelerator reduce the late-age strength of the mix.
- In order to ensure that the 18,000 psi compressive strength limit is reached, cement with a high $C_3S$ content should be used. While 52% $C_3S$ cement (Argos type I/II) was found to provide adequate strengths, a $C_3S$ content of 58% or above is recommended.
- Particle packing optimization led to a sharp decrease in workability, to the mix's ultimate detriment. Packing is an important consideration, but it alone does not determine the suitability of a mix for use as UHPC for accelerated bridge construction.

- Steel fibers are the primary drivers of cost for UHPC mixtures.
- The addition of accelerating admixture does not greatly increase the price of the mix and may be used in cases where higher early strengths are necessary.

# CHAPTER 4. EVALUATION OF GT UHPC AT PRODUCTION-SCALE BATCH SIZES

## 4.1 Background

As discussed in the previous Chapter, the GT UHPC mix has been proven to meet compression strength and workability benchmarks in the 10-quart benchtop mixer. However, further work must be done to ensure that the mix's properties remain the same as the batch size is scaled up and a different style of mixer is used. While a benchtop mixer may suffice for laboratory scale testing, placing UHPC in the field requires much larger batches and the use of a high-shear pan mixer, as seen in Figure 4-1. Furthermore, the workability of the GT UHPC mix has not been established with steel fibers in the mix. This chapter will serve to establish a mixing procedure for field use of GT UHPC and provide further data on compressive strength and workability once fibers have been added to the mix.

**Figure 4-1: UHPC being mixed in a high-shear pan mixer in the field**

### 4.1.1 The Impact of Mixer Type on UHPC

The major consideration when changing mixers is the consideration of mixing energy imparted by the mixer [57]. When mixing concrete, energy from the mixer is imparted to disperse the mix components and hydrate the cement paste. An excess of mixing energy, however, will accelerate the reaction of the cement hydration and cause a loss of workability [57, 58], as shown in Figure 4-2. Different mixers impart different amounts of energy based on how they operate, but in general the optimal mixing time to achieve high workability and dispersion in UHPC is between 10 and 20 minutes. Mixing times beyond this range can result in porous, less-workable mixes [59]. If the GT UHPC mix is to be used, a proper mixing procedure to reliably produce GT UHPC in this timespan using a high-intensity mixer like those used in the field is necessary.

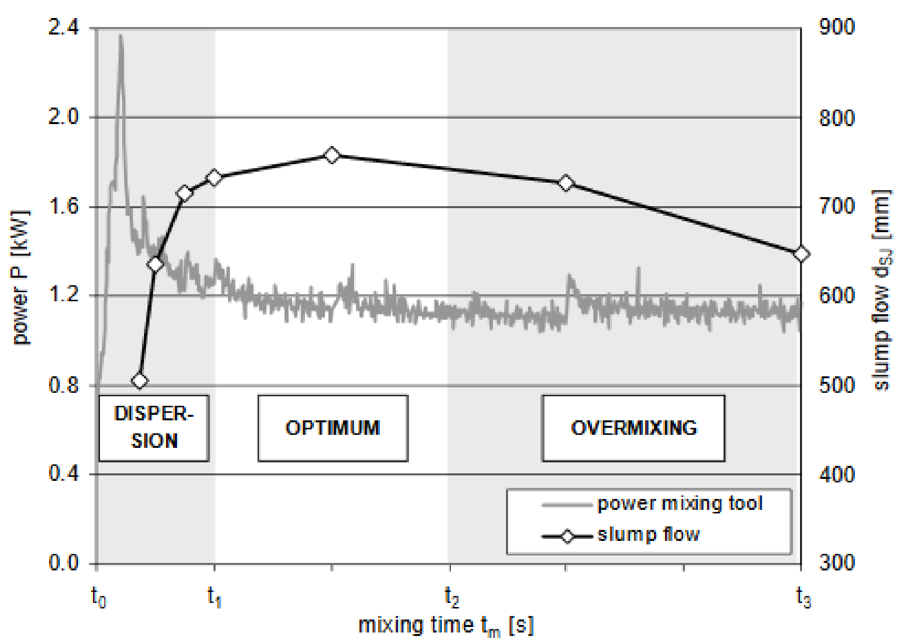



**Figure 4-2: The Effects of Overmixing on Slump Loss [57] (0.7457 kW = 1 hp, 25.4mm = 1 inch)**

### 4.1.2 Mixing Equipment

The mixer that was used for these experiments is an Eirich R08W. This intensive shear pan mixer has an inclined barrel that rotates clockwise. This clockwise rotation carries concrete into a rotor spinning counter-clockwise. A fixed scraper further agitates the concrete as it moves past the rotor. This mixing action is demonstrated by Figure 4-3. This style of mixer has been used previously to produce UHPC by Georgia Tech [60], the Army Corps of Engineers [61], and by researchers abroad [62-64]. This track record demonstrates that this mixer is equivalent to other mixers used for UHPC and is suitable for use in developing mixing procedures for the GT UHPC.

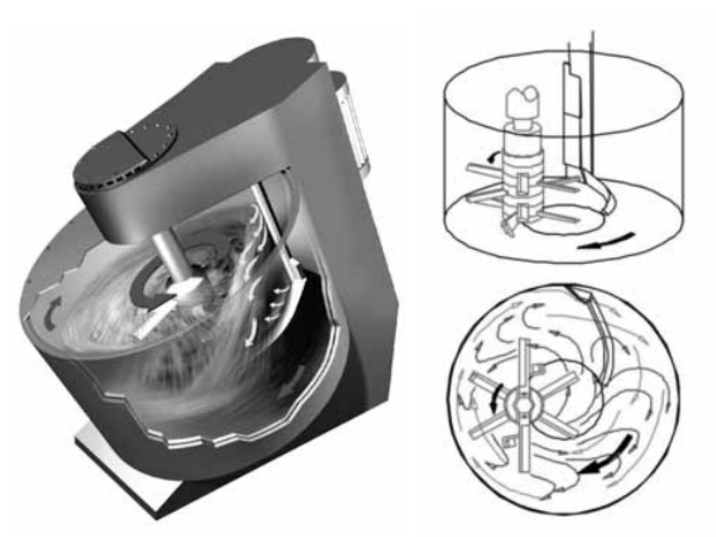


**Figure 4-3: Mixing Action of the Eirich R08W Mixer** [62]

### 4.1.3 Steel Fibers

Steel fibers are a necessary inclusion in UHPC in order to provide tensile and flexural strength. The addition of steel fibers causes a decrease in concrete workability [50, 65] and good workability is necessary to ensure proper dispersion of the fibers [66, 67]. Too much workability, however, will cause the fibers to segregate from the mixture [67]. Because the small-scale mix development of GT UHPC did not involve fibers, it is imperative that the effects of fiber addition be observed in a large-scale setting.

The fibers used in this mix are brass-coated steel fibers 13 mm in length and 0.2 mm in diameter. They have a nominal tensile strength of 2,750 MPa (398 ksi), a Young's modulus of 200,000 MPa (29,000 ksi), and are produced in Georgia (Bekaert; Rome, Georgia) [68]. This size and brand of fiber is very common in UHPC production as these fibers are used in every type of UHPC that is commercially available [69-71] and their short length relative to other fibers allows for improved performance when dosed as a percentage of the mix volume [71].

**Figure 4-4: A Worker Adds Fibers to the UHPC Mixer in the Field**

### *4.1.4 Further Mix Trials*

Once a proper mixing procedure had been established for the GT UHPC, different sources of sand from around the state were acquired in order to test the suitability of alternate aggregate sources. The baseline GT UHPC uses masonry sand from southern Georgia, so masonry sands from both northern (River Sand Inc, Buford, Georgia) and central (Butler Sand, Butler, Georgia) Georgia were acquired in order to evaluate their suitability for use in UHPC. Additionally, a coarser river sand for use in general construction was acquired from the same southern quarry as the southern masonry sand. The particle size distributions and material data of these sands are shown in Table 4-2 and Figure 4-5. These sands were compared to the previously-used south Georgia masonry sand (GT-UHPC). These mixes were given names corresponding to their sands. GT-C, GT-N, and GT-RS corresponded with the central masonry sand, the northern masonry sand, and the southern river sand, respectively. Additionally, a version of the GT-RS mix was performed in which silica fume replaced the metakaolin in order to see how the mix would perform without metakaolin. This mix design is given in Table 4-1.

**Table 4-1: The GT-RS-SF Mix**

| **Material** | **Quantity** |
|---|---|
| Type I Portland Cement | 1,248 lb/yd$^3$ |
| Class F Fly Ash | 387 lb/yd$^3$ |
| Silica Fume | 100 lb/yd$^3$ |
| South Georgia River Sand | 1,997 lb/yd$^3$ |
| Superplasticizer (BASF 7920) | 320 mL/ft$^3$ |
| Water/Binder: 0.18 | |

**Table 4-2: Alternative Sand Data**

| Sieve Size | Percent Passing (%) | | |
|---|---|---|---|
| | Northern Masonry Sand | Central Masonry Sand | South Georgia River Sand |
| #4 | 100 | 100 | 99.39 |
| #8 | 100 | 99.97 | 95.24 |
| #16 | 98.92 | 99.05 | 81.8 |
| #30 | 84.55 | 87.11 | 49.58 |
| #50 | 33.71 | 41.85 | 13.3 |
| #100 | 3.93 | 6.7 | 1.19 |
| #200 | 0.23 | 0.21 | 0.2 |
| **Fineness Modulus** | **1.79** | **1.65** | **2.59** |
| **Specific Gravity (ASTM C128)** | **2.4** | **2.63** | **2.65** |
| **Absorption Capacity (ASTM C128)** | **1.1%** | **0.93%** | **0.53%** |

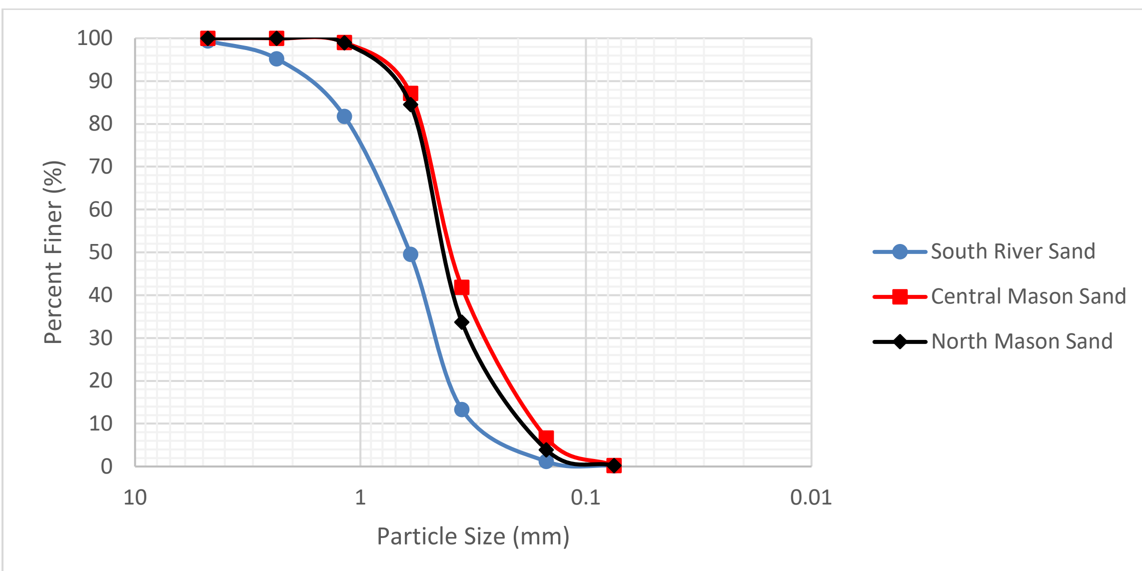



**Figure 4-5: Gradation Curves for Alternative Sands**

### 4.1.5 *Qualifications for Testing*

As with the laboratory-scale experiments, each mix was evaluated based on its compression strength and flow measurements. In a departure from the laboratory scale tests, however, the compression specimens for the large-scale test were cast in 10 cm x 10 cm x 10 cm (3.93 inch x 3.93 inch x 3.93 inch) cubic molds. These molds, shown in Figure 4-6, were selected over more conventional cylindrical specimen shapes because a cubic shape provides plane, parallel sides without the need for grinding.

Nine specimens were cast for each mix performed. Twenty-four hours after casting the specimens were demolded and transferred to a 73°F curing tank filled with saturated lime water. Compression tests were performed at 3, 7, and 28 days with three specimens being tested on each date. Each cube was placed under compression at a rate of 0.6 MPa per second (87 psi/s) in accordance with British Standard EN 12390 for 10 cm concrete cubes [72]. This standard was used due to the absence of standards for cubic specimens of this size in the United States.


**Figure 4-6: 10cm Compression Specimens Being Cast**

## 4.2 Mixing Procedure Development

### *4.2.1 Procedure Development*

In previous work at Georgia Tech, the rotor speed on the mixer was limited to 35 rotations per minute (RPM) for the duration of the mix [60]. Other research has shown, however, that a hybrid mixing approach that combines both high and low speed mixing speeds can help reduce overmixing and decrease mixing time [57]. In order to determine which mixing procedure is optimal, three different mixing procedures were tested for use with the GT UHPC. The first was mixed entirely at 250 RPM, which will be referred to as "GT-1". Another mix, "GT-2", was mixed entirely at 35 RPM. The third mix was mixed in two stages- the dry materials were mixed at 250 RPM and mixing speed was reduced to 35 RPM upon the addition of water. This mix was referred to as "GT-3". The changes to mix procedure are the only changes made to these mixes - compositionally they are all identical GT UHPC mixes. The GT-UHPC mix design is shown again in Table 4-3, this time in the quantities necessary to batch one cubic foot of concrete. The complete mix procedure for each mix and the associated nomenclature is given in Table 4-4.

**Table 4-3: GT-UHPC Mix Design Used for GT-1, GT-2, and GT-3**

| Material | Quantity |
|---|---|
| Type I Portland Cement | 46.20 lb/ft$^3$ |
| Class F Fly Ash | 14.33 lb/ft$^3$ |
| Metakaolin | 3.70 lb/ft$^3$ |
| Masonry Sand | 73.96 lb/ft$^3$ |
| Superplasticizer (BASF 7920) | 320 mL/ft$^3$ |
| Steel Fibers | 9.80 lb/ft$^3$ |
| Water/Binder: 0.18 | |

**Table 4-4: Large Scale Mixing Procedures**

| Mix Procedure | Mixing Speed (RPM) | | |
|---|---|---|---|
| | GT-1 | GT-2 | GT-3 |
| Mix sand and metakaolin for 2 minutes | 250 | 35 | 250 |
| Add fly ash and cement, mix for 1 minute | 250 | 35 | 250 |
| Add water over the course of 30 seconds and let mix for 30 seconds | 250 | 35 | 35 |
| Add HRWR and mix for 8 minutes | 250 | 35 | 35 |
| Add half of the steel fibers and mix for 2 minutes | 250 | 35 | 35 |
| Add remaining steel fibers and mix for 2 minutes | 250 | 35 | 35 |

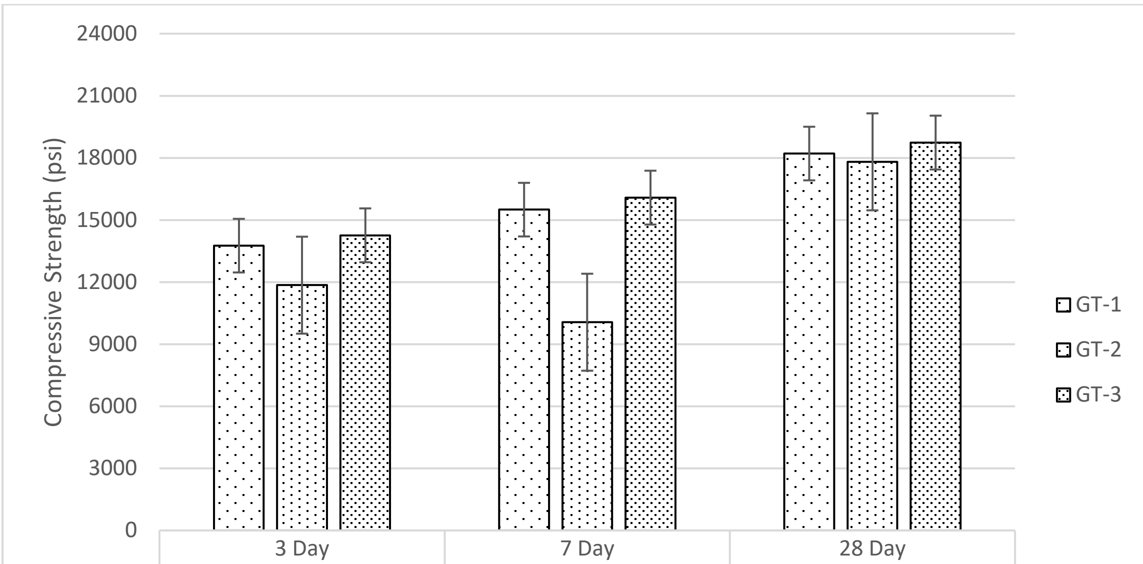
### *4.2.2 Mixing Observations*

The GT-1 mixing process proved to be very ineffective. As the UHPC became cohesive, the high speed of the rotor began to rebuff the concrete away rather than mix it. As a result, the mixture remained in a stiff and unworkable ring. In an effort to cast specimens, the mix time was extended and additional superplasticizer was added. In total, GT-1 was mixed for 30 minutes and contained 450 mL of superplasticizer, up from the 320 mL initially planned. GT-1 achieved self-consolidating flow with an 8.25-inch flow on the flow plate.

The mixing process for GT-2 and GT-3 went much smoother. The lower rotor speed allowed concrete to reach the blades of the rotor and increased the agitation of the concrete. GT-2 achieved a 9-inch flow, while GT-3 achieved an 8 ¾-inch flow.

### *4.2.3 Compression Test Results*

The compression test results for each mixing procedure are given in Figure 4-7.

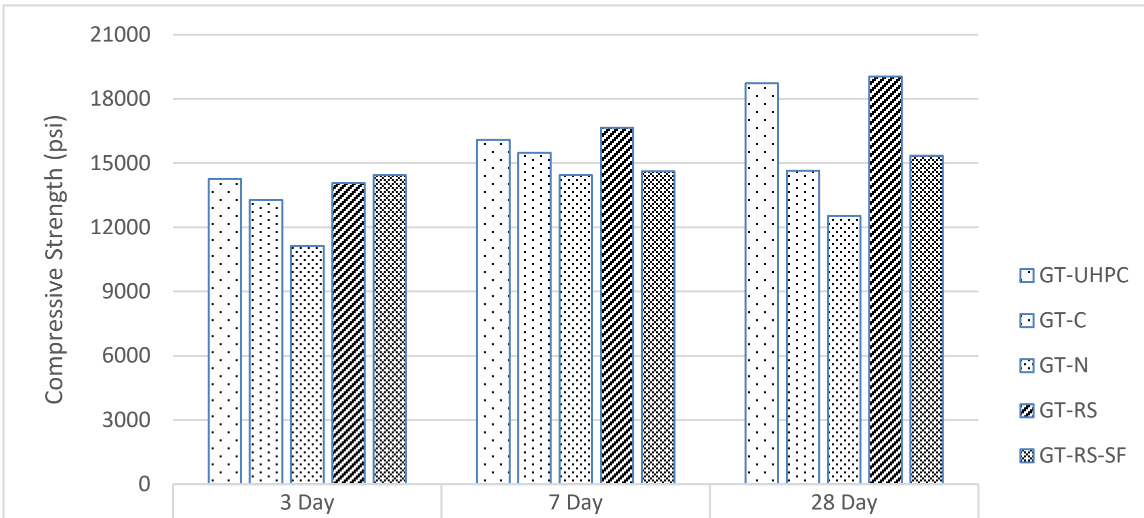



| | 3 Day | 7 Day | 28 Day |
|---|---|---|---|
| GT-1 | 13760 | 15500 | 18210 |
| GT-2 | 11850 | 10060 | 17810 |
| GT-3 | 14260 | 16080 | 18740 |

**Figure 4-7: Mix Process Compression Test Results**

## 4.3 Full-scale Mix Trials

This round of trials compared the usage of difference sand sources for GT UHPC by replacing the fine aggregate with masonry sand from central (GT-Central) and northern (GT-N) Georgia. In addition, the southern Georgia river sand was included as a point of comparison (GT-RS) and to see if the larger sand sizes would lead to lower strengths in the larger samples. Finally, the GT-RS mix was repeated with the addition of silica fume in place of metakaolin to determine compare the effect of metakaolin vs silica fume (GT-RS-SF). The compression results of these tests are shown in Figure 4-8 and mix data is shown in Table 4-5.




| | 3 Day | 7 Day | 28 Day |
|---|---|---|---|
| GT-UHPC | 14260 | 16080 | 18740 |
| GT-C | 13270 | 15480 | 14650 |
| GT-N | 11130 | 14440 | 12530 |
| GT-RS | 14070 | 16660 | 19050 |
| GT-RS-SF | 14440 | 14620 | 15350 |

**Figure 4-8: Compression Data for Sand Trials**

**Table 4-5: Mix Data from Sand Trials**

| Mix Components | Mix Name | | | |
|---|---|---|---|---|
| | **GT-C** | **GT-N** | **GT-RS** | **GT-RS-SF** |
| Cement ($lb/yd^3$) | 1248 | 1248 | 1248 | 1248 |
| Fly Ash ($lb/yd^3$) | 387 | 387 | 387 | 387 |
| Metakaolin ($lb/yd^3$) | 100 | 100 | 100 | 0 |
| Silica Fume ($lb/yd^3$) | 0 | 0 | 0 | 100 |
| Sand ($lb/yd^3$) | 1997 (Central Masonry Sand) | 1997 (Northern Masonry Sand) | 1997 (Southern River Sand) | 1997 (Southern River Sand) |
| Water ($lb/yd^3$) | 312.25 | 312.25 | 312.25 | 312.25 |
| w/cm | 0.25 | 0.25 | 0.25 | 0.25 |
| w/b | 0.18 | 0.18 | 0.18 | 0.18 |
| Superplasticizer ($L/yd^3$) | 13.5 | 20.52 | 8.91 | 9.99 |
| Mix Time | 24 Minutes | 32 Minutes | 16 Minutes | 19 Minutes |
| Flow | 7 3/4" | 6" | 8 1/2" | 7" |

## 4.4 Discussion and Conclusions

### *4.4.1 Mix Process Development Discussion*

From the experiments, it was observed that the inclusion of steel fibers did not affect the ability of the UHPC to reach a self-consolidating state at the dosage of superplasticizer determined by the small-scale mixing trials. Both GT-2 and GT-3 mixing procedures produced self-consolidating UHPC with the inclusion of fibers.

The workability issues, extended mixing time, and need for additional superplasticizer eliminated GT-1 as a feasible mixing process. Despite the extended mixing time and increased dosage of superplasticizer, however, the early-age strength of GT-1 was higher than GT-2. In fact, GT-2 failed to reach the 14,000 psi compressive strength benchmark by

7 days, achieving only 10,000 psi compressive strength at that age. GT-3 was the only mixing procedure that reached both the 14,000 psi 3-day strength benchmark and the 18,000 psi 28-day strength target.

The difference in strength values between the GT-2 procedure and the others is believed to be related to the dispersion of the metakaolin in the mix. Both GT-1 and GT-3 blended the sand and metakaolin at high speeds, imparting more energy to break apart agglomerations of metakaolin. This dispersion of metakaolin has been shown to increase its pozzolanic effects by exposing a higher surface area of metakaolin to the mix [73]. Because it produces a mix that meets strength targets, does not require additional superplasticizer, and stays within the preferred mixing timeframe of 10 to 20 minutes it is recommended that the GT-3 mixing process be adopted for the production of GT UHPC.

### *4.4.2 Alternative Sand Trials Discussion*

Of the sands tested, the North Georgia masonry sand performed the worst when used in the GT UHPC mix. The GT-N mix required an extended mixing period and the addition of 137.5% more superplasticizer than was initially planned for. Despite this high amount of superplasticizer, the mix still only achieved 6 inches of flow and had low workability. The compressive strengths for the mix were also the lowest of all mixes tested, with no strength development between the 7 and 28-day compressive tests. The northern masonry sand was also the poorest quality sand evaluated. It contained many platy minerals and organic inclusions that were visible to the naked eye.

The Central Georgia Masonry sand performed slightly better than the northern sand, but was still unsatisfactory. The GT-C mix required less additional mixing time and required only a 56% increase in superplasticizer dosage over the GT UHPC specification. This sand also provided a more workable mix, achieving a 7 ¾-inch flow result. However, compressive strengths still fell short of the 18,000 psi compressive strength requirement and this mix displayed the same lack of strength development between 7 and 28 days as the GT-N Mix.

The South Georgia river sand had the highest performance of all sands tested. The total mix time was identical to the GT-UHPC at 16 minutes. The mix was self-consolidating with an 8 ½-inch flow and the GT-RS mix only required an additional 3% dosage of superplasticizer over the GT UHPC specification. The GT-RS mix was also the only alternative mix design tested that met the 14,000 psi 3-day strength and 18,000 psi 18-day strength targets. The GT-RS-SF mix variant had high early age, meeting the 14,000 psi 3-day strength. However, it showed very little strength gain at 7 and 28 days and required additional mixing time and superplasticizer over the regular GT-RS mix. The results of the GT-RS-SF mix indicate that metakaolin provides an advantage over silica fume in the GT UHPC mix.

The sieve analysis gradations for the sands tested are shown in Table 4-6. The highest performing sands - and indeed the only sands that could be used to meet strength requirements - were the masonry and river sands from Southern Georgia. It can be seen in Table 4-6 that these sands are very clean, with a very low content of fine sand. The southern masonry sand only contains 1.53% material finer than a #100 sieve, while the river sand contains only 1.19% material finer than a #100 sieve. Additionally, both the central and northern masonry sands contain roughly double the amount of material that passes a #50 sieve than the southern masonry sand. These results indicate that having a fine sand only serves as a detriment to GT UHPC.

**Table 4-6: Gradation Data for All Sands**

| Sieve Size | Percent Passing (%) | | | |
|---|---|---|---|---|
| | Northern Masonry Sand | Central Masonry Sand | South Georgia River Sand | South Masonry Sand |
| #4 | 100 | 100 | 99.39 | 100 |
| #8 | 100 | 99.97 | 95.24 | 99.99 |
| #16 | 98.92 | 99.05 | 81.8 | 95.08 |
| #30 | 84.55 | 87.11 | 49.58 | 63.98 |
| #50 | 33.71 | 41.85 | 13.3 | 17.99 |
| #100 | 3.93 | 6.7 | 1.19 | 1.53 |
| #200 | 0.23 | 0.21 | 0.2 | 0.29 |
| **Fineness Modulus** | **1.79** | **1.65** | **2.59** | **2.21** |
| **Specific Gravity (ASTM C128)** | **2.4** | **2.63** | **2.65** | **2.65** |
| **Absorption Capacity (ASTM C128)** | **1.1%** | **0.93%** | **0.53%** | **0.93** |

### *4.4.3 Conclusions*

The conclusions from the full-scale experiments are summarized as follows:

- In order to generate a workable mixture that meets strength targets and can be produced in a reasonable amount of time, the dry ingredient stages of the mix should be completed at high speeds to aid in dispersion of the binder particles.
- Metakaolin is superior to silica fume for use at the dosage levels required in the GT UHPC mix as it provides higher strengths and requires a shorter mixing duration

- Coarser sands such as the South Georgia river sand may be used in GT UHPC to great success. It is confirmed that both the masonry sand and the river sand from the South Georgia sand supplier can be used to mix UHPC.
- If alternate sands are to be used in GT UHPC they must have a very low content of materials passing #100 sieve. Additionally, it is recommended that the amount of material finer than a #50 sieve also be limited. Any alternate sands in consideration should also be tested in a mixing trial to investigate their effect on workability and compressive strength.

# CHAPTER 5. UHPC MIX DESIGN UTILIZING HIERARCHICAL MACHINE LEARNING

## 5.1 Motivation

Despite the growing body of work relating to the development of ultra-high performance concrete mixes, the process of designing a UHPC mix is still a highly iterative process. A test-matrix approach requires many labor- and material-intensive mixes and re-mixes to determine the effects of different variables on the mix's overall properties. Particle packing optimization approaches require iteration as well. The Compressible Particle Model requires iteration to adjust the mix design to an appropriate *K* value, whereas the Modified Andersen and Andreasen Model requires iteration to achieve the "ideal" gradation curve. Both of these models also require additional mix trials to determine if the mix developed meets strength and workability targets.

Instead of starting these processes from the beginning for each UHPC design, it would be advantageous to directly apply data gained from previous research to generate an appropriate mix design. For these purposes, a machine learning approach provides an attractive avenue for mix design. By aggregating previous work on UHPC the machine learning model can predict mix designs that will meet the required criteria. In collaboration with researchers at Carnegie Mellon University, this chapter reports an investigation on the use machine learning as effective tool for UHPC mix design.

## 5.2 Background

Machine learning has been defined as "…a diverse collection of powerful techniques utilized to identify relationships in data, allowing for modeling and optimization of complex systems [74]." These techniques involve developing algorithms that analyze data sets to determine relationships between the data points in order to predict future outcomes. Machine learning methods have recently seen increased attention from the field of concrete research, with researchers using machine learning to predict the compressive strengths of lightweight concrete mixes [75] and to predict the carbonation potential of reinforced concrete [76]. Most recently, machine learning has been found to predict the field compressive strength of concrete more accurately than current laboratory models [77].

### *5.2.1 Hierarchical Machine Learning*

In a traditional machine learning approach, datasets consisting of thousands to millions of data points are analyzed and the algorithm infers relationships between the data points that it later uses to inform its predictions. While UHPC development is a growing field, there is nowhere near enough published data to compile a database large enough to evaluate through traditional machine learning methods. The purpose of the enormous databases used in traditional machine learning approaches is to prevent the algorithm from perceiving erroneous relationships between data points. Hierarchical Machine Learning (HML) is an approach in machine learning that seeks to reduce the dependence on database size by combining "domain knowledge" with the traditional machine learning approach. A visual comparison between traditional machine learning and HML approach is shown in Figure 5-1

This "domain knowledge" is selected by the developer of the model and is based on well-established causal relationships that have been well-studied. As an example, a developer can direct the algorithm to give higher statistical significance to the water to cement ratio of the mix because this is a relationship that is well-established to affect the compressive strength of concrete. In this way, the developer of an HML model can direct the model to focus on relationships that are known to be important.

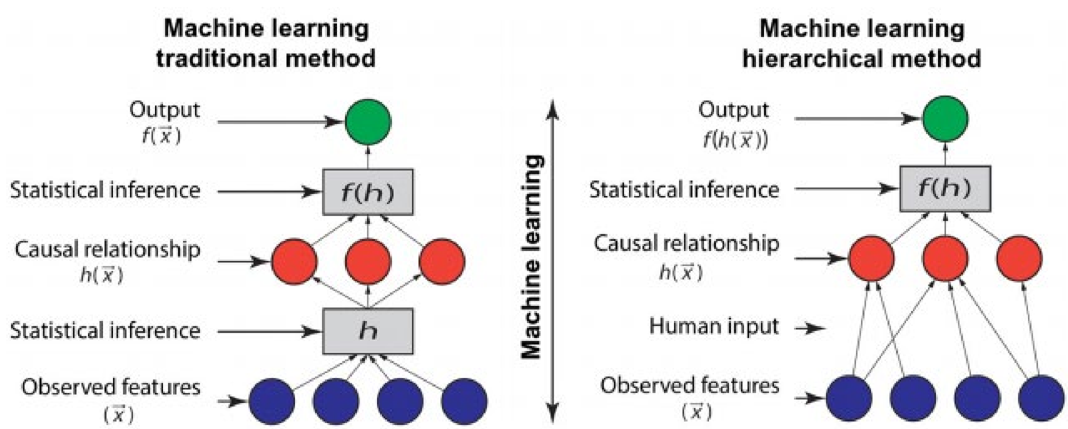



**Figure 5-1: A Diagram Showing How The Hierarchical Model Allows The Incorporation of Domain Knowledge Before Predicting Outputs [74]**

### 5.3 Development of an HML Model for UHPC Design

In a collaborative effort, the author worked with Mr. Christopher Childs, a Ph.D. student at Carnegie Mellon University part of Dr. Newell Washburn's research group, to develop an HML model for predicting UHPC mix designs. This model incorporated data from its training datasets in consideration with the domain knowledge provided by the research team in order to generate mixes that it predicted would provide the highest 28-day compressive strength.

### *5.3.1 Datasets for Use in the Model*

The author compiled a database of UHPC mixtures from published literature, from which the collaborators at CMU selected for use in the HML model. Two datasets were chosen for training the model. The first training dataset was a set of eight mixes from "Metakaolin in the Formulation of UHPC" by Tafraoui et. al [37]. These eight mixes were cured at three different temperatures, giving a total of 24 data sets. The second training set was composed of the 53 mix designs tested in "Prediction of Fresh and Hardened State Properties of UHPC: Comparative Study of Statistical Mixture Design and an Artificial Neural Network Model" by Ghafari et al [78]. These mixes were cured at two different temperatures, giving a total of 106 additional data sets. The database used for training the HML model has been submitted alongside this thesis and can be found in Georgia Tech's SmartTECH database under the title "Machine Learning Training Set for UHPC." The eight mix designs from "Ultra-High Performance Concrete and Fiber Reinforced Concrete: Achieving Strength and Ductility without Heat Curing" by Wille et al. [79] were chosen by the Carnegie Mellon team for use in validating the model. The Carnegie Mellon team elected to utilize a Ridge Regression model as it returned the lowest mean squared error of the machine learning model types they analyzed.

### *5.3.2 Mix Design Variables Included in the Data*

All reported mix design parameters from the training mixes were entered into the database for use in the model. The amount of cement, supplementary cementitious materials, filler materials, aggregates, water, superplasticizer, and steel fibers in each mix was recorded. Additionally, the curing temperature and 7- and 28-day compressive strength results of each mix were recorded. The reported average particle diameter for all components was also recorded. For particles which had no listed average diameter, the values listed in Table 5-1 were assumed based on existing laboratory data.

**Table 5-1: Assumed Particle Sizes for Cement and SCMs**

| Particle | Assumed Average Size (micron) |
| --- | --- |
| Cement | 15 |
| Fly Ash | 25 |
| Silica Fume | 0.2 |
| Metakaolin | 12 |
| Nanosilica | 0.05 |

### *5.3.3 Domain Knowledge Incorporated*

Six parameters were chosen for inclusion as domain knowledge in the model. These six parameters are the equivalent cement content, the particle packing of the mixture, the water film thickness, the superplasticizer content, the fiber content, and the curing temperature. These parameters were selected for consideration based on established knowledge of cement chemistry relationships to direct the HML model what to focus on. The algorithm evaluated these parameters and assigned its own significance to them.

- *Equivalent cement content.* The concept of an "equivalent cement" value first appeared in a paper on the thermal control of mass concrete placements [80]. In this application, it serves as an estimate of the approximate amount of heat generated by a concrete that includes SCMs. The equation, produced in the paper and shown in Equation 5.1, normalizes each mix component into an "equivalent" weight of cement based on its assumed heat generation. For example, class F fly ash is assumed to produce half as much heat as regular Portland cement, so the amount of class F fly ash is multiplied by 0.5. The original equivalent cement equation did not include metakaolin, so it was added for use with this research. This concept was incorporated as domain knowledge as a way of measuring the reactivity of a mix design in the absence of calorimetry data. The higher the equivalent cement content, the more reactive the mix is assumed to be.

$$\begin{aligned} &Cement + 0.5(Amount\ of\ Class\ F\ Fly\ Ash) \\ &\qquad + 0.8(Amount\ of\ Class\ C\ Fly\ Ash) \\ &\qquad + 1.2(Amount\ of\ Silica\ Fume) \\ &\qquad + 1.2(Amount\ of\ Metakaolin) + X(Amount\ of\ Slag) \end{aligned} \tag{5.1}$$

*Where X = 1.1 for 0-20% replacement of cement by slag, 1.0 for 20-45% replacement, 0.9 for 45-65% replacement, and 0.8 for 65-80% replacement.*

- *Particle Packing.* Including particle packing as domain knowledge requires an input parameter that will summarize the packing of the mixture in a single, numerical parameter. This need for a single parameter precludes the use of graphical-based modified Andersen and Andreasen model used in Chapter 3.

Instead, the Compressible Particle Model (CPM) is a much better fit for this application. The CPM summarizes the packing of the mixture into a single parameter, *K*. Higher *K* values correspond with denser mixtures and higher compressive strengths. In order to automatically calculate this *K* value, a Python script was developed and included in the model. A version of this Python script and instructions for its use are given in Appendix A.

- *Water film thickness.* The water film thickness is a relationship between the amount of water present in the mixture and the surface area of all particles present in the mixture. A higher water film thickness value corresponds with higher workability and self-consolidating behaviour [81]. For UHPC it is assumed that there is no excess water to fill the voids in the mix, so the water film thickness was calculated according to Equation 5.2.

$$HFT = \frac{\mu_w}{A_s} \tag{2.5}$$

*Where* $\mu_w$ *= The volume ratio of water in the UHPC mixture*
$A_s$ *= The surface area per unit volume of all particles*

- *Superplasticizer content.* The model was directed to evaluate the superplasticizer content, by volume percentage, of all mixes in the database. While superplasticizer lends UHPC its workability, an excess of superplasticizing admixture can cause the strength development to be delayed. Thus, it is important for the HML model to consider the amount of superplasticizer present.

- *Fiber content.* Generally UHPC contains 2-3% steel fibers by volume. Further addition of steel fibers can cause a loss of workability and an increase in entrapped air, leading to lower compressive strengths. For these reasons, the model was directed to consider fiber content as domain knowledge.
- *Curing temperature.* It is well established that curing temperature has a large effect on the compressive strength of UHPC. Higher curing temperatures lead to accelerated strength development and higher overall compressive strengths [69, 82, 83].

## 5.4 Further Constraints and Mix Development

### *5.4.1 Mixes Provided by the HML Model*

Once the model had been trained and validated on the provided datasets and domain knowledge, a list of 15 mix designs that were predicted to generate the highest compressive strengths was generated from the model. These mix designs proved to be unmixable, however, so the following additional constraints were added to the model to control what mixes it developed:

- Sand to cement ratio limited to between 1.0 and 2.0
- Maintain a water to cement ratio between 0.2 and 0.3
- Limit silica fume to 18% of the combined weight of binder materials
- Limit filler materials to 18% of the combined weight of binder materials
- Limit superplasticizer to 10% of the amount of water present in the mix

These recommendations were based on the FHWA's published guidelines for UHPC mix design [21] and from prior laboratory experience. Following these guidelines, the proportional mix designs shown in Table 5-2 were predicted by the model to provide the highest compressive strengths.

**Table 5-2: Initial Proportional Mix Designs (by Weight of Cement)**

| | Mix A | Mix B | Mix C | Mix D | Mix E | Mix F |
|---|---|---|---|---|---|---|
| Cement | 1 | 1 | 1 | 1 | 1 | 1 |
| Silica Fume | 0.219 | 0.219 | 0.255 | 0.264 | 0.132 | 0.305 |
| Steel Fibers | 0.284 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Water | 0.226 | 0.226 | 0.201 | 0.191 | 0.181 | 0.215 |
| Superplasticizer | 0.025 | 0.025 | 0.023 | 0.022 | 0.017 | 0.024 |
| Masonry Sand | 0.000 | 0.000 | 0.000 | 0.000 | 1.169 | 1.577 |
| River Sand | 1.581 | 1.581 | 1.500 | 1.459 | 0.000 | 0.000 |
| 45-micron Limestone | 0.215 | 0.215 | 0.071 | 0.000 | 0.000 | 0.068 |
| Curing Temperature (C) | 20 | 20 | 20 | 20 | 20 | 20 |
| Predicted Strength (MPa) | 254 | 254 | 279 | 275 | 270 | 265 |
| Standard Deviation in Prediction | 6.5 | 6.5 | 11.1 | 11.9 | 11.1 | 11.5 |

These mix designs were not workable either. Because of this, it was decided that superplasticizer would be added until the mixes became both fluid and cohesive in order to determine what sort of strengths these mixes would produce. The final mix designs tested, including additional superplasticizer, total mixing time, and flow test measurements are shown in Table 5-3.

**Table 5-3: Final Proportional Mix Designs (by Weight of Cement)**

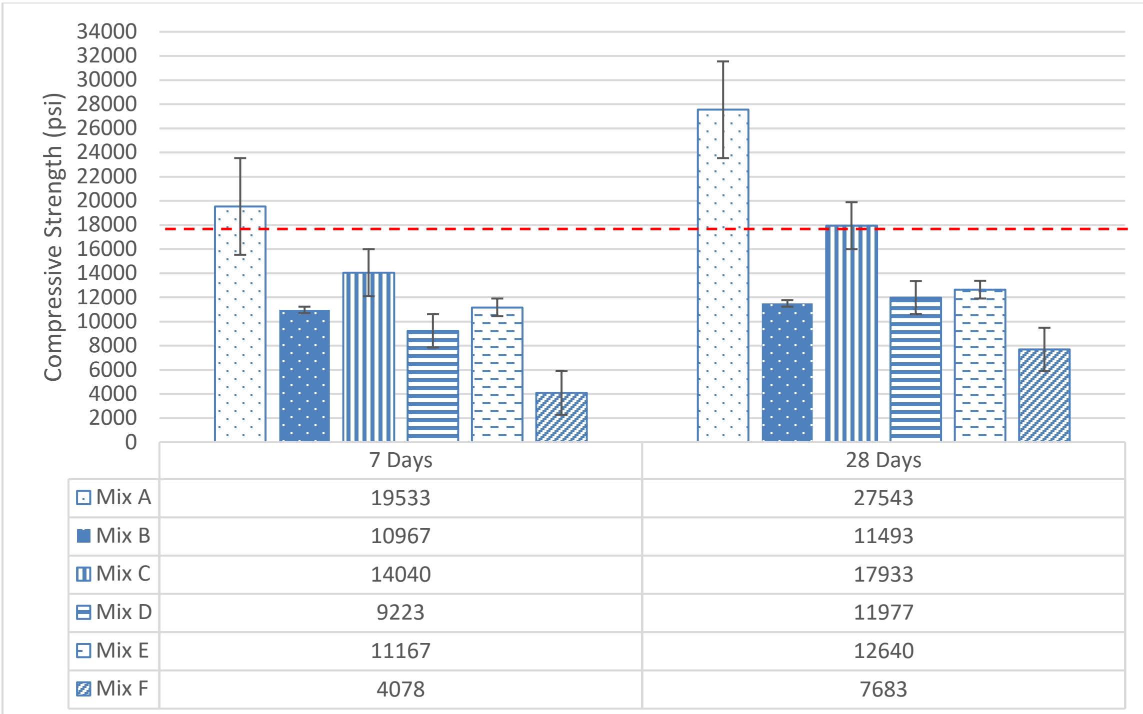
| | Mix A | Mix B | Mix C | Mix D | Mix E | Mix F |
|---|---|---|---|---|---|---|
| Cement | 1 | 1 | 1 | 1 | 1 | 1 |
| Silica Fume | 0.219 | 0.219 | 0.255 | 0.264 | 0.132 | 0.305 |
| Steel Fibers | 0.284 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Water | 0.226 | 0.226 | 0.201 | 0.191 | 0.181 | 0.215 |
| Superplasticizer | 0.031 | 0.031 | 0.062 | 0.101 | 0.056 | 0.137 |
| Masonry Sand | 0.000 | 0.000 | 0.000 | 0.000 | 1.169 | 1.577 |
| River Sand | 1.581 | 1.581 | 1.500 | 1.459 | 0.000 | 0.000 |
| 45-micron Limestone | 0.215 | 0.215 | 0.071 | 0.000 | 0.000 | 0.068 |
| Curing Temperature (C) | 20 | 20 | 20 | 20 | 20 | 20 |
| Predicted Strength (MPa) | 254 | 254 | 279 | 275 | 270 | 265 |
| Standard Deviation in Prediction | 6.5 | 6.5 | 11.1 | 11.9 | 11.1 | 11.5 |
| Mixing Time (minutes) | 30 | 30 | 25 | 27 | 30 | 35 |
| Flow Test (inches) | 4" | 6 1/2" | 5 1/2" | 6" | 6" | 6" |

### *5.4.2 Mixing and Testing Procedure*

All mixes were conducted in 0.03 cubic foot batches in a table top mixer following the an adaptation of the mixing procedures in Table 4-4 from Chapter 4. Additional time was allowed for the mix to come together before fibers were added. As in Chapter 3, the specimens cast for compression testing were 2 inch by 2 inch mortar cubes. There were six specimens cast for each mix, with compression testing occurring at 7 and 28 days. The specimens were loaded in the compression machine at a rate of 18,000 pounds per minute, on average.

## 5.5 Compression Testing Results

The results of the compression tests performed are shown in Figure 5-2.




| | 7 Days | 28 Days |
|---|---|---|
| Mix A | 19533 | 27543 |
| Mix B | 10967 | 11493 |
| Mix C | 14040 | 17933 |
| Mix D | 9223 | 11977 |
| Mix E | 11167 | 12640 |
| Mix F | 4078 | 7683 |

**Figure 5-2: Compression Testing Data for Machine Learning Mixes**

## 5.6 Discussion and Conclusions

### *5.6.1 Discussion*

It can be seen that Mix A provided the highest compression strengths and in fact reaches compressive strengths well above the generally-accepted lower bounds for UHPC compressive strength. This strength comes at great cost, however, due to the 30-minute mixing time and the high percentage of fibers in the mixture. This mix is the only one of the six tested that included fibers, containing around 7% steel fibers by volume of the mix. The usual recommendation for UHPC is 2% steel fibers by volume. This large amount of steel fibers reduced the workability to essentially zero, as can be seen by the four flow test result. These fibers would also serve to make this mix very expensive to produce commercially.

Mix B was identical to Mix A, except fibers were excluded from the mixture. These samples exhibited swelling similar to those seen in Figure 3-7 and exhibited much lower strengths due to this. The swelling is believed to be related to additional porosity from the extended 30-minute mix time necessary for the mix to incorporate. This swelling was not observed in any of the other mixes. The fibers present in Mix A seem to have added enough confinement to prevent this expansion.

Mix C was the second-best performing mix, nearly reaching 18,000 psi compressive strength by 28 days. Mix C also require the second-least addition of superplasticizer. Because the relative amounts of superplasticizer can be difficult to gauge from the proportional mix design, the superplasticizer content per cubic foot is shown in Table 5-4, with the GT Mix and FHWA mixes given for reference.

**Table 5-4: Superplasticizer Content of Each Mix**

| Superplasticizer Content (mL/$ft^3$) | | |
|---|---|---|
| | Planned | Actually Added |
| GT Mix | 320 | 320 |
| FHWA Mixes [21] | ~700 | ~700 |
| Mix A | 483 | 600 |
| Mix B | 483 | 600 |
| Mix C | 483 | 1280 |
| Mix D | 493 | 2220 |
| Mix E | 467 | 1460 |
| Mix F | 500 | 2820 |

Indeed, a negative correlation between superplasticizer content and compressive strength can be observed. Mix F, which required the most superplasticizer to come together also performed the worst of all mixes tested. Likewise, Mix D had the second lowest compressive strength at 7 days, the third lowest compressive strength at 28 days, and also required the second highest admixture dosage.

Mix E presents an interesting case because it performed similarly to Mix D but had far less added superplasticizer. The reduction in strength is believed to be due to Mix E having the lowest water to cement ratio. This reduced cement hydration in turn affected how much the silica fume could contribute to the strength.

### *5.6.2 Conclusions*

The conclusions from the study performed in this chapter are as follows:

- Hierarchical Machine Learning shows promise in developing mix designs that can meet the compressive strength requirements in UHPC, although further refinement to the model must be undertaken.
- Workability of all mixes was poor, indicating that better domain knowledge relating to workability should be added. In particular, more attention should be paid to parameters that affect superplasticizer dosage, as the planned value was consistently lower than what was actually required.
- The expansion observed in mix B should be observed more closely to determine its effect. If it is a result of extended mixing times as believed, efforts should be taken to reduce mixing times.

# CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

## 6.1 Conclusions

The purpose of this research was to evaluate the development of UHPC from materials local to Georgia through a variety of methods. In the first part of the study, a test matrix-approach and a particle packing optimization using the modified Andersen and Andreasen model were used to develop mix designs from local materials. In the second part, the mix design developed in the first part was scaled up to production-scale batches and tested using aggregates from around Georgia. In the final part, a novel type of machine learning called Hierarchical Machine Learning was used to develop mix designs for UHPC. Based on the test data and results, the following conclusions can be drawn:

- Ultra-high Performance Concrete can be made from materials entirely local to Georgia. This concrete surpasses 18,000 psi compressive strength at 28 days without the need for accelerating admixtures and is self-consolidating in nature. This concrete also surpasses 14,000 psi compressive strength by 3 days, allowing it to be used in accelerated bridge construction.
- The GT UHPC mix developed is somewhat sensitive to the fineness of the aggregates present in the mixture. If a different sand source must be used to produce this mix, it is recommended that the material passing a #100 sieve be minimized and a test mix be done to ensure that the sand is an acceptable replacement.

- When mixing the GT UHPC mix, the dry components of the mix should be blended at high speed to aid in the dispersion of metakaolin throughout the mix. Upon the addition of water to the mix, lower mixing speeds should be adopted.
- Hierarchical Machine Learning can be utilized in UHPC mix design by allowing domain knowledge to compensate for the relatively small body of published work relating to UHPC. This HML model is capable of developing mixes that exceed 27,000 psi compressive strength and at the very least provides a good starting-off point for new UHPC development.

## 6.2 Recommendations for Future Work

This research was successful in producing a concrete that meets the high compressive strengths necessary for classification as UHPC, but work remains to be done in the following areas:

- Compressive strength is an important characteristic of UHPC, but it is not the only factor that matters for the material. Work should be done to evaluate the GT UHPC mix's tensile strength, flexural strength, and shrinkage and ensure that they fall within reasonable ranges.
- Further investigation is necessary into the relationship between aggregate fineness and the superplasticizer dosage and compressive strength of the GT UHPC mix. The acceptable limits for aggregate fineness must be determined, and additional sources of aggregates that will be compatible with the GT UHPC Mix should be identified.

- The HML model should be further refined to better account for the workability of the mixture, as it has shown promise for developing ultra-high strengths but has not produced a mix design that was workable without the need for additional superplasticizer. Additional domain knowledge should be found that can be used to better predict what dosage of superplasticizer is required to meet self-consolidating behaviour while still meeting compressive strengths.

# APPENDIX A. PYTHON CODE FOR FINDING THE PACKING INDEX *K* IN THE COMPRESSIBLE PARTICLE MODEL

```
#Packing Parameters
beta=0.74 #Maximum virtual packing density(beta)
phi=0.64 #Actual packing density of the mixture

#Mix Input
diameters1=[300,11,8,0.18] #List all particle diameters present here
proportions1=[0.25,0.37,0.25,0.12] #List the volume percentage of each
of the above diameters here
wandsp1=0.21 #Enter the volume percentage of water and superplasticizer
here


#Function to get the packing index K

def packingindex(diameters,proportions,wandsp):
    K=0
    n=len(diameters)
    for i in range(0,n):
        gammai=0 #virtual density
        b=0
        B=0
        Sb=0 #Sum involved in gamma (wall effect)
        a=0
        A=0
        Sa=0 #Sum involved in gamma (loosening effet)
        for j in range(0,i):
            #print(diameters[i],diameters[j])
            b=1-(1-(diameters[i]/diameters[j]))**1.5
            B=(1-beta+(b*beta*(1-(1/beta))))*proportions[j]
            Sb=Sb+B
        for j in range(i+1,n):
            #print(diameters[i],diameters[j])
            a=(1-(1-(diameters[j]/diameters[i]))**1.02)**0.5
            A=(1-a*(beta/beta))*proportions[j]
            Sa=Sa+A
        gammai=beta/(1-Sb-Sa)
        #print(gammai)
        phi=wandsp
        K=K+((proportions[i]/beta)/((1/(phi))-(1/gammai)))
        #print(K)
    return K
```

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